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RELIABILITY-BASED COMPARATIVE LIFE EXPECTANCY ASSESSMENT OF PATROL BOAT HULL STRUCTURES

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16. Abstract

The estimation of an absolute life expectancy is a complex process and the results are expected to have relatively large levels of uncertainty. In this study, a comparative study is undertaken between two different patrol boats. This is an approach which will result in a higher confidence level because certain common factors to the boats can be eliminated by assuming them to be at constant normal levels. The study is limited to the critical forward bottom plating and takes into account the differences in material, plate dimensions, operational profile, structure and loading of the two vessels. Two failure modes, plastic plate deformation and fatigue, are considered and a novel approach to wastage is included. Many factors affect the structural life of a boat. They include structural type, operational profile, structural details, loads, inspection and maintenance, design methods, safety factors, corrosion and environmental factors. These factors have four types of uncertainty; namely, physical randomness, statistical and model uncertainties, and vagueness, which are addressed by a reliability-based structural life assessment methodology.

The overall objective of the report is to present the reliability-based structural life assessment methodology, and then use it to evaluate and compare the structural performance of the forward bottom plating of the two patrol boats. The results of the evaluation are presented in the form of graphs and tables in order to facilitate the comparative evaluation. The study features a computer-based format which allows parametric sensitivity analysis of several variables including the size of the plating panel, thickness, operational profile and loading. The sensitivity of the structural life expectancy of the forward bottom plating to variations in these parameters is evaluated. The results are summarized using figures and charts.

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METRIC CONVERSION FACTORS

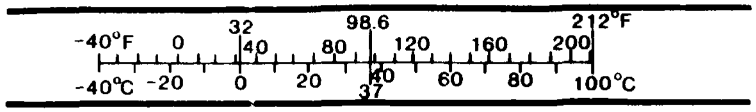
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10 286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

The estimation of an absolute life expectancy is a complex process and the results are expected to have relatively large levels of uncertainty. In this study, a methodology for structural life expectancy was developed, validated and calibrated using the performance records of the Cape-Class patrol boat, and a comparative study was undertaken between the Island and Heritage-Class patrol boats. The comparative study is expected to result in relatively higher confidence levels than an absolute life expectancy assessment, because certain common factors to the boats can be eliminated by assuming them to be at their constant normal levels. The study is limited to the critical forward bottom plating and takes into account the differences in material, plate dimensions, operational profile, structure and loading of the two vessels.

The estimation of structural life expectancy can be based on selected failure modes. All possible failure modes of the Island, Heritage and Cape-Class patrol boats were identified. The most critical failure modes, based on experiences of the U.S. Coast Guard and the fundamentals of naval architecture, were determined to be plate plastic deformation and fatigue. A novel approach to include plate corrosion and wastage was developed as a component of the methodology. Structural life expectancy based on these two failure modes was determined for the forward bottom plating of the three boat classes.

Many factors affect the structural life of a boat. They include structural type, operational profile, structural details, loads, inspection and maintenance, design methods, safety factors, corrosion, and environmental factors. These factors have four types of uncertainty; namely, physical randomness, statistical and model uncertainties, and vagueness. All can be addressed by a reliability-based structural life assessment methodology.

A methodology for structural life assessment was developed. The methodology is based on probabilistic analysis using reliability concepts and the statistics of extremes. The methodology results in the probability of failure of the boat structural system according to the identified failure modes as a function of time, i.e., structural life. The results can be interpreted as the cumulative probability distribution function (CDF) of structural life. Due to the unknown level of statistical correlation between failure modes, limits or bounds on the CDF of the structural life the structural system were established. The limits correspond to the extreme cases of fully correlated and independent failure modes. An interactive computer program was developed to perform these calculations that allows parametric sensitivity analysis of structural life due to variations in several variables.

The analytical results presented herein are based on several important assumptions. The assumptions include the following:

1. The test results performed by the U.S. Coast Guard R&D Center to determine the plate stresses at critical locations of the Island-Class patrol boat under different sea state/boat speed combinations. Based on these tests, the ratios of design to the mean value of the maximum pressure for different sea state/boat speed combinations were determined.
2. A random operational profile that is defined by the total number of operational hours per year, and the percents of boat usage in head seas at different sea state/boat speed combinations.
3. The design structural drawings and details as provided by the U.S. Coast Guard R&D Center.
4. The statistical characteristics of strength and load effects as reported in previous studies.
5. Definition of the end of structural life as determined based on current practices and experiences of the U.S. Coast Guard.
6. The critical structural locations for the three boats that were selected for the purpose of performing this study.
7. Selected statistical characteristics of plate wastage rate based on the literature search.
8. Damage observed during any inspection is not corrected until it reaches the level of "significant damage" as defined for the end of structural life of the forward bottom plating of the boats.

The developed analytical model was calibrated using reported structural performance information of the Cape-Class patrol boat. The model resulted in probabilities of failure with good agreement with reported damage at about the end of its structural life. The resulting calibrated model was then used for the comparative analysis of the forward bottom plating of the Island and Heritage-Class patrol boats. Based on this analysis, the life expectancy of the Island-Class patrol boat in the fatigue failure mode was determined to be slightly better than the Heritage-Class patrol boat. However, the probabilities of failure in fatigue for both boats were within the acceptable limits. On the other hand, the Heritage-Class patrol boat was determined to be significantly better than the Island-Class patrol boat in the plate deformation failure mode. In the structural system analysis, the failure mode with larger probabilities of failure significantly drives the results. Therefore, the system's probabilities for the Island-Class patrol boat are driven by the plate deformation failure mode, whereas the system's probabilities for the Heritage-Class patrol boat are driven by the fatigue failure mode.

A parametric sensitivity analysis of the developed analytical model was performed on the Island-Class patrol boat. The parameters that are considered in this sensitivity analysis include the simulation cycles, size of the plating panel, thickness of the plating, operational profile, number of operational hours per year, loading profile, fatigue details, and plate failure criteria. The results of the parametric analysis are summarized in figures that can be used for considering possible structural changes to the boat.

1. INTRODUCTION

The U.S. Coast Guard has procured the Island-Class patrol boat (110 ft.) under the "parent craft" concept, rather than designing it for a specified design life. This class of boats is currently seeing service in various locations from Puerto Rico to Alaska. The boats have had a high average service rate so far (2167 hours/year) and some hull structural problems have been noted in the bow and bottom plating. In addition, the U.S. Coast Guard has designed the Heritage-Class patrol boat (120 ft.) and is awaiting the construction of the first boat. In the meantime, several Cape-Class patrol boats are being decommissioned after many years of service.

The main objective of the proposed study is to perform a reliability-based comparative hull structure life expectancy analysis of these patrol boats. The service record information for these boats is utilized to calibrate the analytical reliability model developed. The estimation of the structural life is limited to the critical forward bottom plating of the boats. Many factors affect the structural life expectancy of the hull structure. These factors include design parameters, design safety factors, design methods, boat type, structural details, materials, construction methods and quality. The loading which the vessel experiences, including vessel weight, water pressures, waves, and engine and propeller vibrations also affect the life expectancy of the structure. Maintenance practices and levels, and inspection methods are the owner's tools to attempt to control structural life expectancy and also need to be included. These factors can have different types of uncertainties associated with them. There are generally four types of uncertainty associated with these factors: (1) Physical randomness in magnitude and time of occurrence, (2) statistical uncertainties due to using limited amount of information in estimating the characteristics of the population, (3) model uncertainties due to inaccuracies in the prediction models, and (4) vagueness in the definition of the factors or in assessing their effects on life.

The estimation of an absolute life expectancy is a complex process and the results are expected to have relatively large levels of uncertainty, i.e., small levels of confidence. The estimation of a relative (or a comparative life expectancy) is an easier and more sensible task. By performing a comparative study of the life expectancy, any factors which have very large levels of uncertainty, but which can be assumed to apply to both boats, can essentially be eliminated. This is accomplished by assuming them to be at some constant normal levels for both boats. This still allows the effect of those factors to be included, without affecting the relative life expectancies of each boat.

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2. FAILURE MODES

2.1 DEFINITION OF POTENTIAL FAILURE MODES

One of the first tasks that must be tackled for any type of boat is to identify and categorize all of the potential failure modes of the structure. In this study, the potential failure modes of a typical high performance semi-planing or planing hull boat are described. It is from this initial survey of potential failure modes that the specific areas for further investigation are chosen. The failure modes are categorized according to the severity of consequences resulting from the failure. It should be noted that operator error, such as running aground, and damage due to hostile attacks are not considered.

2.1.1 Catastrophic Failure Modes

These are failure modes in which the consequence of failure is the possible loss of the vessel. Such potential failure modes include:

1. Brittle fracture of the deck or bottom as a result of rapid crack growth from a smaller flaw.
2. Rupture of bottom plating as a result of impact with the water surface during slamming.

2.1.2 End of Serviceability Failure Modes

These failure modes are not as immediately dangerous as the catastrophic modes, but represent conditions which would make the vessel unserviceable for normal operations. They typically are so expensive to repair that it might be economically more feasible to take the vessel out-of-service rather than repair it. Possible failure modes in this category are:

1. Ductile yielding of gross panel of the deck or bottom such that significant plastic deformation has taken place. This can result in misalignment of shafts or gun-mount train rings, excessive vessel hogging or sagging, and areas of extremely large stress concentrations which could lead to catastrophic failure.
2. Buckling of deck or bottom panels. This mode is not just the buckling of panels of plating between stiffeners, but rather the overall buckling of gross panels between transverse stiffening. Invariably such deformations lead to reduced load carrying capacity among the remaining structural members and is a precursor to some types of catastrophic failure.
3. Cracking of multiple structural details in a primary load carrying area. Again, it is not a catastrophic failure by itself, but rather an indication of potential weaknesses in the structure which might recur even if the symptoms are repaired.

2.1.3 Serviceability Limiting Failure Modes

Failure modes in this category are those which are troublesome enough that a vessel either must be taken out-of-service for a short time in order to perform repairs or which cause some limit on operational performance until the next scheduled repair period. Some possible failure modes in this category are:

1. Fatigue cracking of local details which run into the skin of the ship and penetrate it.
2. Fatigue cracking of engine mounts, or other structural supports of machinery or equipment which might cause reduced operational capability.
3. Fracture of major structural components which could possibly lead to more serious consequences.

2.1.4 Non-Limiting Failure Modes

This category is for those failure modes which are not likely to cause a major degradation in the vessel's mission, but could possibly affect vessel performance. Some possible failure modes are:

1. Buckling of local plating between stiffeners in the underwater hull. Local plate buckling is not a reason to take a vessel out of service, but it could have an effect on the hydrodynamic performance of the vessel.
2. Yielding of local plating between stiffeners as a result of combined in-plane and out-of-plane loads. The consequences are the same as for buckling of the plating.
3. Bimetallic corrosion of the deckhouse-hull connection in steel ships with aluminum deckhouses.

2.1.5 Nuisance Failure Modes

Nuisance failure modes are those which either affect the aesthetic appearance of the vessel or which taken individually do not represent problems which could be classified as being in one of the other categories. An example of this type of failure mode is the plastic deformation of the side shell plating (above the waterline) resulting from combined loads. This would give the classic "hungry horse" look to the vessels sides. It represents no real threat to the performance of the vessel, but is considered unsightly.

2.2 SELECTION OF FAILURE MODES

Only a few of the failure modes listed in the previous section are ones which would likely cause a boat to be considered as unfit for further service. Also, some of the potential failure modes are not very likely to occur given the material used in its construction or the scantlings required by the design authorities responsible for the vessel. As a consequence, only a few of the failure modes might eventually lead to a level of damage significant enough to ultimately threaten the serviceability of the boat.

In order to identify which failure modes to investigate in this study, a series of meetings were held with representatives from the U.S. Coast Guard Headquarters, Office of Engineering and Office of Acquisition. The two most likely failure modes were selected based on input from them, survey reports from the Coast Guard SSMEB inspections of the 95 ft WPB's (M. Rosenblatt & Sons, 1985), and structures related casualty reports for the Island-Class WPB's.

The reports and first hand information from the individuals confirmed that because of the relatively robust scantlings of the structural framework of typical WPB's and the comparatively small in-plane loads shown in the quasi-static balance in extreme waves (Ayyub and White, 1987), gross panel buckling would not be considered as a potential problem. Rupture of bottom plating due to impact with waves was ruled out as a problem based on historical evidence and the enormous pressures required to rupture a steel plate of the geometry in the three WPB's. Again because of the relatively small in-plane loads experienced by this type of boat, all buckling modes of failure were considered unlikely. This conclusion is born out in the history of the Coast Guard's 95 ft and 82 ft WPB's where the only buckling damage reported could be traced to collisions.

The process of elimination then leaves the most likely potential failure modes as ductile plastic deformation of gross panels, ductile plastic deformation of individual plate panels, and various fatigue related modes. Again because of the relatively robust scantlings of the structural framework, ductile plastic deformation of the gross panel is considered unlikely. However, the forward bottom plating of the Island-Class patrol boat is somewhat thin, indicating a potential problem with individual plate panel deformation. This conclusion is supported by previous studies (Ayyub and White, 1987 and 1988) as well as the casualty report records.

Fatigue cracking of structural details is a problem in all types of seagoing vessels. Antoniou (1977) reported that "there is practically no ship entirely free of cracks". In the U.S., Jordan and Cochran (1978) and Jordan and Knight (1980) estimated that there were an average of 86 structural detail failures per ship for the ships which they inspected. This potential failure mode was chosen for investigation because it represents one of the most common types of structural failure and one which can possibly grow to catastrophic proportions if unrestrained.

Both potential failure modes identified in this study represent serviceability related modes of failure. That is, the failures will not lead directly to loss of the boat, but may limit performance or endurance in some manner. Relating this limited serviceability to a definition for end of useful structural life is covered in the next section.

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3. DEFINITION OF END OF STRUCTURAL LIFE

What determines an end of structural life is, usually, an economic factor. Once the cost of maintaining the structural system exceeds a specified budgeted amount, the replacement of the structure is necessary. The scope of this study does not include economic analysis of the structural system of the boat, or its maintenance schedule and cost. The end of structural life of the boats was defined based on approximate economic analysis and meetings with officials from the Coast Guard Headquarter's Office of Engineering and Office of Acquisition. In these meetings, it was decided that structural life can be terminated once the level of boat maintenance exceeds the amount currently being budgeted. For the significant modes of structural failure and the three boats, this definition was translated into the following criteria:

3.1 PLASTIC PLATE DEFORMATION

The end of structural life of the boat is defined, for the plate deformation failure mode, as having to replace more than about 20 % of the panels in a specified area at the end of any inspection and maintenance period (hereafter called inspection period). Plate panels are to be replaced when the ratio of plastic deformation to plate thickness is greater than or equal to 3.0. The inspection schedule of the boat includes the warranty inspection at the end of the first year followed by regular inspections every two years.

This definition is based on the resources currently allocated for repair and steel replacement for the boats' lifetime maintenance cycle. When more than about 20 % of the panels need to be replaced, the allocated costs are exceeded and a boat meets the economic definition of end of structural life.

The critical regions for the boats were defined as the forward bottom plating. These regions are defined in the following sections for the three boats and are summarized in Table 3-1.

3.1.1 Island-Class Patrol Boat:

1. Critical Region: The critical region is defined between and including bulkheads 13 and 17, and two longitudinals (inclusive) above the keel bar on each side of the boat. This region is between stations 2 and 3-1/3. The total number of sections between these bulkheads is 7. The distance between them is 3x47 + 23.5 = 164.5 in. The region percent of the water line length is 164.5/(12x104) = 13.1%. The panel size within the region is 11.75 in.(width) x 23.5 in.(length). The total number of panels within the region is 7x2x2 = 28 plates. The total area of the plates is about 28x11.75x23.5/144 = 53.7 ft^2. The size of the plate is 7#, which has a design thickness of 0.160 in and a mean thickness of 0.1610 in. The allowable range for the thickness is [0.1554 in, 0.1714 in]. The mid-range

is 0.163 in. Therefore, the mean to mid-range thickness ratio is 0.1610/0.163 = 0.988.

2. Significant Damage: Significant damage is defined in terms of the ratio of plastic deformation to plate thickness of at least 3, and the failure of at least 6 plates out of 28 plates. Therefore, percent plate failure of at least 6/28 = 21.4%.

3.1.2 Heritage-Class Patrol Boat:

1. Critical Region: The critical region is defined between and including bulkheads 9 and 14, and two longitudinals (inclusive) above the keel bar on each side of the boat. This region is between stations 2-2/3 and 4-1/3. The total number of sections between these bulkheads is 5. The distance between them is 5x3.5x12 = 210 in. The region percent of the water line length is 210./(12x110) = 12.7%. The panel size within the region is about 12.0 in.(width) x 42. in.(length). The total number of panels within the region is 5x2x2 = 20 plates. The total area of the plates is about 20x12.0x42./144 = 70.0 ft^2. The size of the plate is 7.65#, which has a design thickness of 0.1875 in, and an allowable range of [0.1735 in, 0.2175 in]. The mid-range is 0.1995 in. Using the same mean to mid-thickness ratio of the Island-Class boat for the Heritage-Class boat, the mean thickness is determined to be 0.988x0.1955 = 0.193 in.

2. Significant Damage: Significant damage is defined in terms of the plastic deformation to plate thickness of at least 3, and the failure of at least 0.214x20 = 4 out of 20 plates = 20%.

3.1.3 Cape-Class Patrol Boat:

1. Critical Region: The critical region is defined between and including bulkheads 15 and 27, and two longitudinals (inclusive) above the keel bar on each side of the boat. This region is between stations 1-2/3 and 3. The total number of sections between these bulkheads is 2. The distance between them is 2x72 = 144 in. The region percent of the water line length is 144./(12x90) = 13.%. The panel size within the region is about 18 in.(width) x 72. in.(length). The total number of panels within the region is 2x2x2 = 8 plates. The total area of the plates is about 8x18x72./144 = 72 ft^2. The size of the plate is 7.65# without galvanizing, which has a design thickness of 0.1875 in, and an allowable range of [0.1735 in, 0.2175 in]. The mid-range is 0.1995 in. Using the same mean to mid-thickness ratio of the Island-Class boat for the Cape-Class boat, the mean thickness is determined to be 0.988x0.1955 = 0.193 in. The thickness of the plate does not include the thickness of galvanizing. The critical region definition presented herein agrees well with the region used by Rosenblatt (1985).

2. Significant Damage: Significant damage is defined in terms of the plastic deformation to plate thickness of at least 3, and the failure of at least 0.214x8 = 2 out of 8 plates = 25%.

Table 3-1. Critical Region and Significant Damage for Plate Deformation

Parameter	Island	Heritage	Cape
Critical Region:			
Frames	13 to 17	9 to 14	15 to 27
# of Longitudinals	2	2	2
Stations	2 to 3-1/3	2-2/3 to 4-1/3	1-2/3 to 3
Length	164.5 in	210. in	144. in
% Length	13.1 %	12.7 %	13. %
Plate Size	11.75x23.5 in	12.0x42. in	18.x72. in
Area	53.7 ft^2	70.0 ft^2	72. ft^2
# of Panels	28	20	8
Plate Size	7#	7.65#	7.65#
Mean Thickness	0.161 in	0.193 in	0.193 in
Design Thickness	0.160 in	0.1875 in	0.1875 in
Significant Damage:			
Deflection Ratio	at least 3	at least 3	at least 3
Min. # of Plates	6	4	2
Total # of Plates	28	20	8

Table 3-2. Critical Region and Significant Damage for Fatigue

Parameter	Island	Heritage	Cape
Critical Region:			
Frames	13 to 17	9 to 14	15 to 27
# of Longitudinals	2	2	2
Stations	2 to 3-1/3	2-2/3 to 4-1/3	1-2/3 to 3
Length	164.5 in	210. in	144. in
% Length	13.1 %	12.7 %	13. %
No. of Fatigue Details			
25	12	0	0
36(Long'l)	76	136	16
36(Transverse)	0	16	8
4	14	0	0
10A	4	0	0
20	0	4	0
21	0	4	0
26	0	4	0
39(38)	0	4	8
28F(28)	0	16	4
51(51V)	0	16	0
11	0	0	4
49(51 or 52)	0	0	4
Total count	106	200	44
Significant Damage:	One or More details for all boats		

3.2 FATIGUE FAILURE

For this potential failure mode, the end of structural life of a boat was defined as the development of one or more fatigue failures of a critical detail within the same specified critical region of the vessel as defined for plate deformation. The critical fatigue details of each boat were identified and categorized based on the Ship Structure Committee Report Number 318 (SSC-318) Munse, et al (1982). A fatigue detail was considered not critical, if the detail stress function (see Section 5.2.3) was approximately zero, and such a detail was not counted in Table 3-2.

3.2.1 Island-Class Patrol Boat:

The critical region for the Island-Class patrol boat is defined in Figure 3-1. The critical region includes four connection types which were identified as susceptible to fatigue and brittle fracture due to wave loading and water pressure. These four types of connections are identified as connection types A, B, C and D. These connection were discussed and analyzed in detail by Ayyub and White (1988). The connections are briefly described in the following:

1. Connection Type A: The structural connection between a water-tight longitudinal (i.e., edge of water tank) and the shell plating is considered as Connection Type A. The weld connection is continuous without scallops. This connection can be found in Drawing No. 110 WPB 117-001 Sheet 4 of 12, entitled Transverse Sections, Frames 13 1/2 thru 16. The most critical location in this connection is the weld between the web of the longitudinal stiffener and the shell. This weld can be classified as fatigue detail no. 4 according to the classification by Munse, et al in SSC-318 (1982). This detail is referred to, in this study, as Detail IA-4. The total number of this type of detail in the critical region is 14.
2. Connection Type B: The second structural connection is between a longitudinal stiffener and a web frame. This connection includes the weld between a longitudinal stiffener and a 2x2 clip which connects the longitudinal stiffener to the frame. This connection is shown in Drawing No. 110 WPB 117-001 Sheet 11 and 12 of 12 as Structural Details No. 9 and 21, respectively. The weld between a longitudinal stiffener and a frame can be classified as fatigue detail no. 25 according to the classification by Munse, et al (1982). This detail is referred to, in this study, as Detail IB-25. The total number of this type of detail in the critical region is 12 each.
3. Connection Type C: The first structural connection is the weld between the longitudinal stiffener with two-inch scallops and the shell (i.e., plating). This connection is shown in Structural Details 7 and 9 in Drawing No. 110 WPB 117-001 Sheet 11 of 12, called Transverse Sections, Misc. Details. This connection can be classified as fatigue detail no. 36 according to the classification by Munse, et al in SSC-318 (1982). The detail is referred to, in this study, as Detail IC-36. The total number of this type of detail in the critical region is 76.

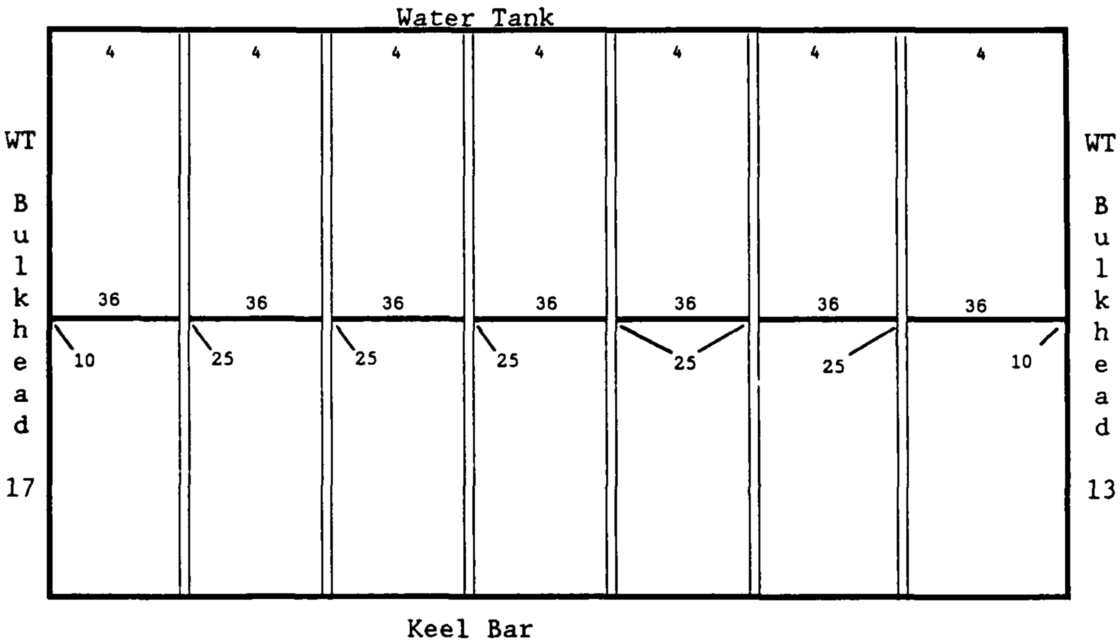

Figure 3-1. Critical Region for the Island-Class Patrol Boat

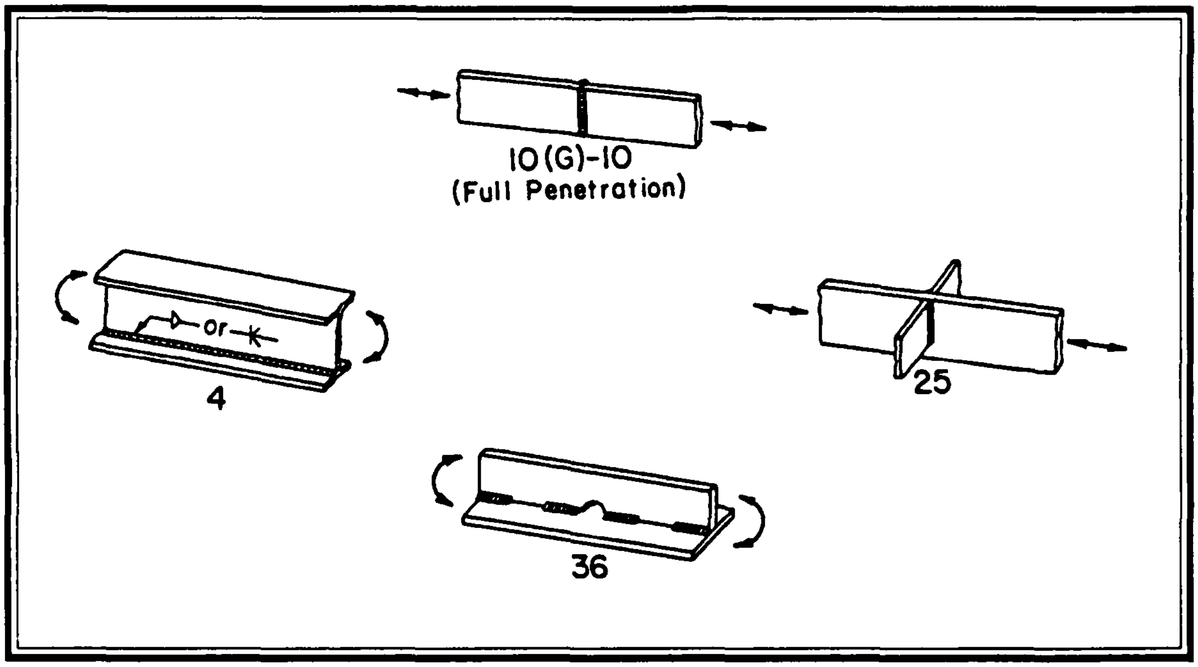

Figure 3-2. Local Fatigue Details for the Island-Class (Munse, 1982)

4. Connection Type D: This structural connection is between a longitudinal stiffener and a water tight bulkhead. Because the bulkhead is water tight, it is made continuous. The continuity of the longitudinal stiffener is provided by a gusset plate. This connection is shown as Structural Detail No. 110 WPB 117-001 Sheet 11 of 12. The most critical location in this connection is the weld between the web of the longitudinal stiffener and the gusset plate. The weld can be classified as fatigue detail no. 10A according to the classification by Munse, et al in SSC-318 (1982). This detail is referred to, in this study, as Detail ID-10A. The total number of this type of detail in the critical region is 4.

Therefore, in the critical region of the Island-Class patrol boat, there are four local fatigue detail types, 36, 25, 4 and 10A. The local fatigue details are shown in Figure 3-2.

3.2.2 Heritage-Class Patrol Boat:

The critical region for the Heritage-Class patrol boat is defined in Figure 3-3. The critical region includes three connection types which were identified as susceptible to fatigue and brittle fracture due to wave loading and water pressure. These three types of connections are identified as connection types A, B and C. The connections are briefly described in the following:

1. Connection Type A: The first structural connection is the weld between the longitudinal stiffener with scallops and the shell plating. This connection is shown in Drawing No. 120WPB 802-007 Sheet 1 of 2, called Transverse Sections, Misc. Details. This connection can be classified as fatigue detail no. 36 according to the classification by Munse, et al in SSC-318 (1982). The detail is referred to, in this study, as Detail HA-36. The total number of this type of detail in the critical region is 136.
2. Connection Type B: This structural connection is between a longitudinal stiffener and a water tight bulkhead. Because the bulkhead is water tight, it is made continuous. The continuity of the longitudinal stiffener is provided by a gusset plate. This connection is shown in Drawing No. 120WPB 802-009 Sheet 1 of 1. The most critical location in this connection is the weld between the web of the longitudinal stiffener and the gusset plate. These welds can be classified as fatigue detail numbers 20, 21, 26 and 39 according to the classification by Munse, et al in SSC-318 (1982). These details are referred to, in this study, as Details HB-20, HB-21, HB-26 and HB-39. The total number of these details in the critical region is 4 each.

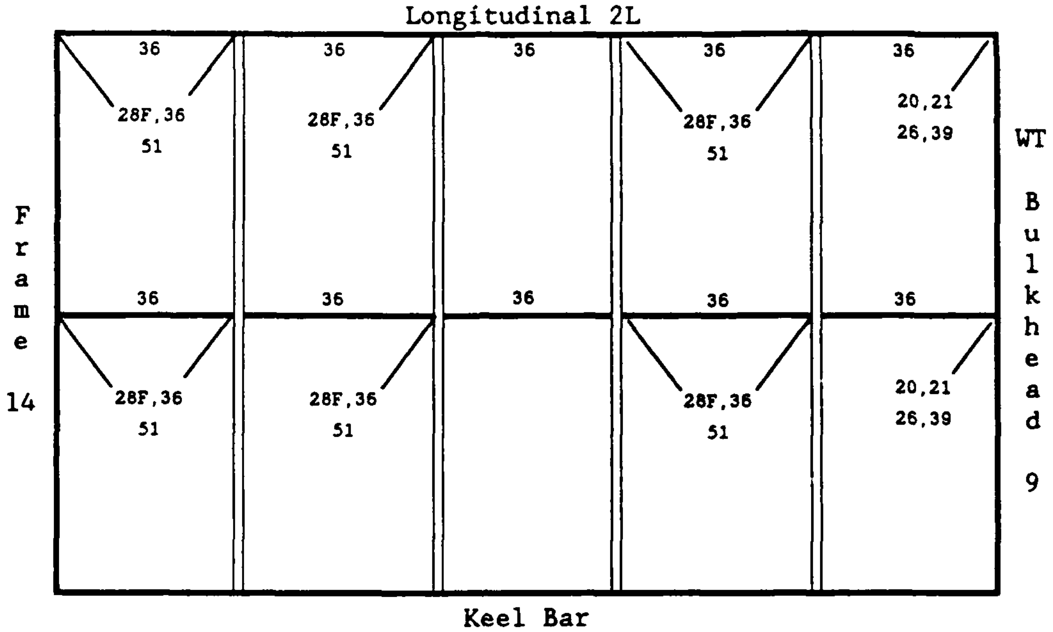

Figure 3-3. Critical Region for the Heritage-Class Patrol Boat

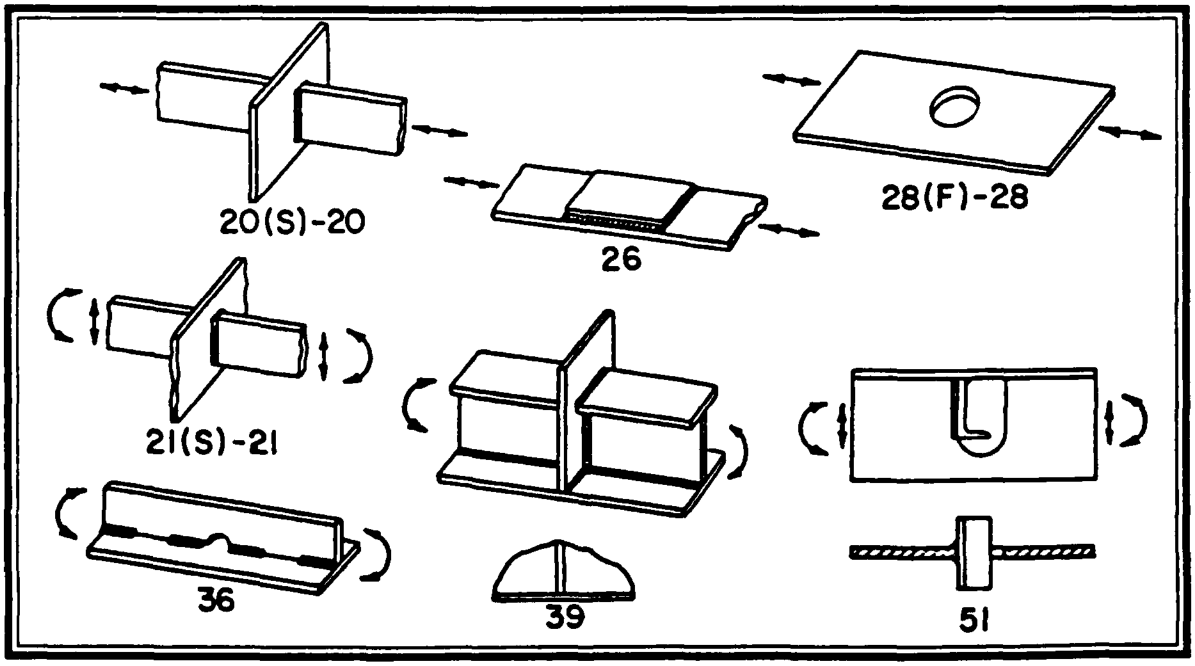

Figure 3-4. Local Fatigue Details for the Heritage-Class (Munse, 1982)

3. Connection Type C: The third structural connection is between a longitudinal stiffener and a web frame. This connection includes the weld between a longitudinal stiffener and a web frame, and the opening in the web frame. This connection is shown in Drawing No. 120WPB 802-007 Sheet 1 and 2. The local fatigue detail at this connection can be classified as fatigue detail numbers 36, 28F and 51 according to the classification by Munse, et al in SSC-318 (1982). These details are referred to, in this study, as Detail HC-36, HC-28F and HC-51. The total number of these details in the critical region is 16 each.

Therefore, in the critical region of the Heritage-Class patrol boat, there are seven local fatigue detail types, 36, 20, 21, 26, 39, 28F and 51. The local fatigue details are shown in Figure 3-4.

3.2.3 Cape-Class Patrol Boat:

The critical region for the Cape-Class patrol boat is defined in Figure 3-5. The critical region includes three connection types which were identified as susceptible to fatigue and brittle fracture due to wave loading and water pressure. These three types of connections are identified as connection types A, B and C. The connections are briefly described in the following:

1. Connection Type A: The first structural connection is the weld between the longitudinal stiffener and the shell plating. There are small cutouts for plate weld seams and limber holes at the intersection of the web frame and the longitudinals. These connections are shown as Sections "D-D" and "F-F" in Drawing No. 95WPB 1103 Sheet 1 of 1, called Web and Longitudinal Framing. This connection can be classified as fatigue detail no. 36 according to the classification by Munse, et al in SSC-318 (1982). The detail is referred to, in this study, as Detail CA-36. The total number of this type of detail in the critical region is 16.
2. Connection Type B: This structural connection is between a longitudinal stiffener and an oil/water tight bulkhead. Because the bulkhead is oil/water tight, it is made continuous. The continuity of the longitudinal stiffener is provided by welding the longitudinal to the bulkheads. This connection is shown as Section "F-F" in Drawing No. 95WPB 1103 Sheet 1 of 1. The most critical location in this connection is the weld between the web of the longitudinal stiffener and the bulkheads. This weld can be classified as fatigue detail number 39 according to the classification by Munse, et al in SSC-318 (1982). These details are referred to, in this study, as Details CB-39. The total number of the detail in the critical region is 8.

3. Connection Type C: The third structural connection is between a longitudinal stiffener and a web frame. This connection includes the weld between a longitudinal stiffener and a web frame, and around the cutout in the web frame. This connection is shown in Drawing No. 95WPB 1103 Sheet 1 and 1 as Structural Detail No. 7. The local fatigue details at this connection can be classified as fatigue detail numbers 36, 28F and 49 according to the classification by Munse, et al in SSC-318 (1982). These details are referred to, in this study, as Detail CC-36, CC-28F and CC-49. The total number of these details in the critical region are 8 for CC-36, and 4 each for CC-28F and CC-49.
4. Connection Type D: The fourth structural detail is the butt weld of the longitudinals numbers 1 and 2 which takes place 6 inches aft of frame 15. The connection is shown in Drawing NO. 95WPB 1103 Sheet 1 of 1 in the Expanded view of plating and Longitudinal. The local fatigue detail at this section can be classified as fatigue detail number 11 according to SSC-318. This detail is referred in this study as Detail CD-11. The total number of this type of detail in the critical region is 4.

Therefore, in the critical region of the Cape-Class patrol boat, there are four local fatigue detail types, 36, 39, 28F, 49, and 11. The local fatigue details are shown in Figure 3-6.

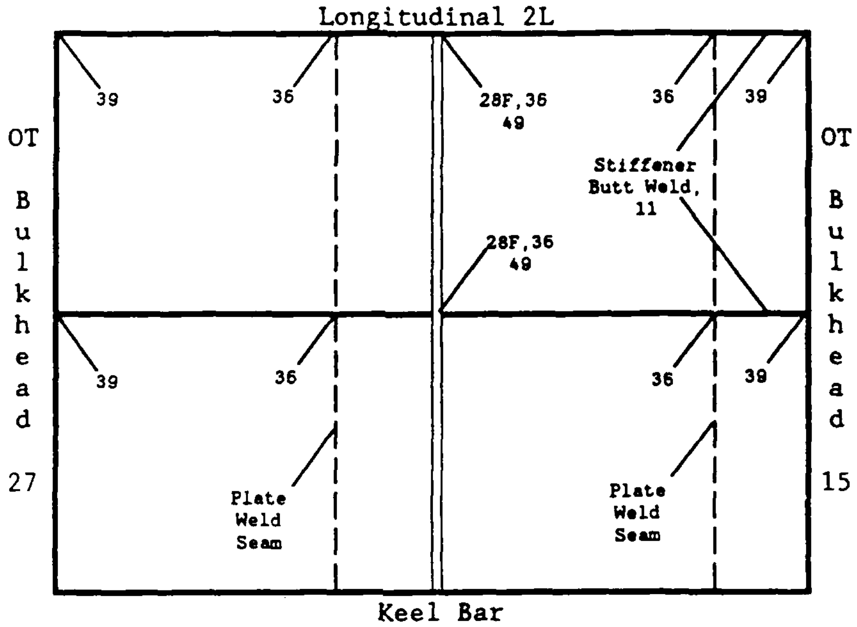

Figure 3-5. Critical Region for the Cape Class Patrol Boat

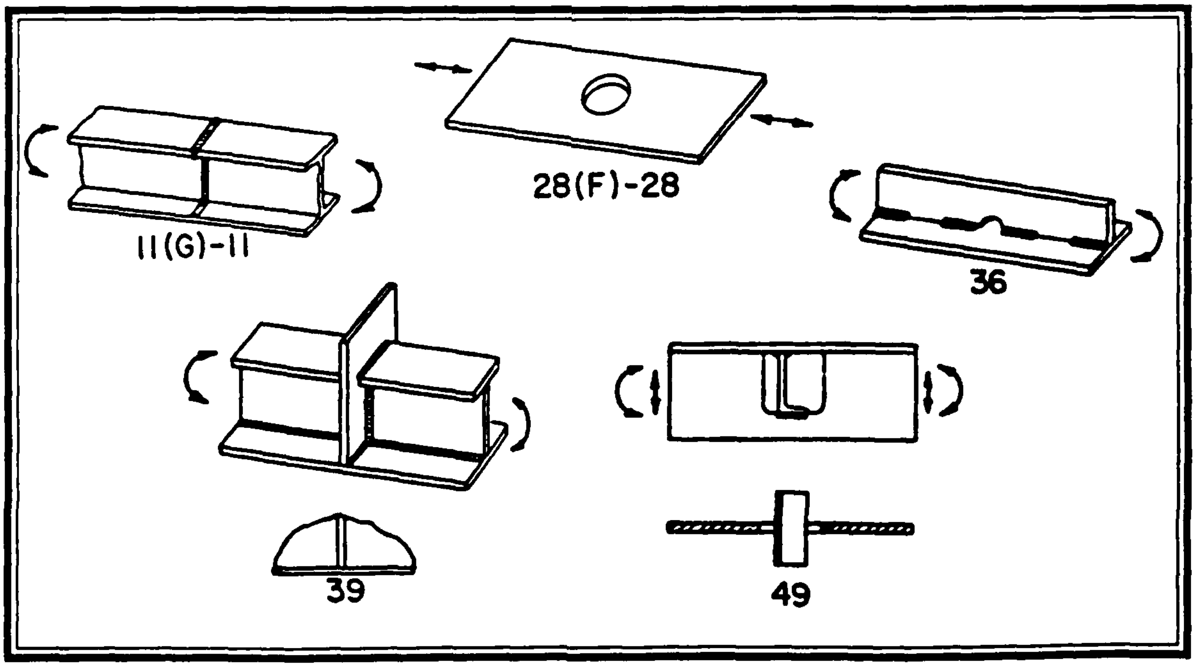

Figure 3-6. Local Fatigue Details for the Cape-Class (Munse, 1982)

4. METHODOLOGY OF STRUCTURAL LIFE ASSESSMENT

4.1 STRUCTURAL RELIABILITY ASSESSMENT

The performance function that expresses the relationship between the strength and load effect of a structural member according to a specified failure mode is given by

$$Z = g(X_1, X_2, \ldots, X_n) \tag{4-1}$$

in which the X_i's, $i=1, \ldots, n$, are the basic random variables, with $g(.)$ being the functional relationship between the basic random variables and failure (or survival). The performance function can be defined such that the limit state, or failure surface, is given by $Z = 0$. The failure event is defined as the space where $Z < 0$, and the survival event is defined as the space where $Z > 0$. Thus, the probability of failure can be evaluated by the following integral:

$$P_f = \int\int \ldots \int f_{\mathbf{X}}(X_1, X_2, \ldots, X_n)\, dx_1\, dx_2 \ldots dx_n \tag{4-2}$$

where $f_{\mathbf{X}}$ is the joint density function of $\mathbf{X} = (X_1, X_2, \ldots, X_n)$, and the integration is performed over the region where $Z < 0$. Because each of the basic random variables has a unique distribution and they interact, the integral of equation 4-2 cannot be easily evaluated. A probabilistic modeling approach of Monte Carlo computer simulation with Variance Reduction Techniques (VRT) can be used to estimate the probability of failure (Ayyub and Haldar 1984, and White and Ayyub 1985).

The strength (or resistance) R of a structural component and the load effect L are generally functions of time. Therefore, the probability of failure is also a function of time. The time effect can be incorporated in the reliability assessment by considering the time dependence of one or both of the strength and load effects. In the following sections the modeling of time dependence of strength and load effects are briefly discussed.

4.2 TIME DEPENDENCE IN STRUCTURAL RELIABILITY ASSESSMENT

4.2.1 Time Dependence of Load Effects

Generally, there are three approaches which can be used to model the time dependence of load effects:

1. Stochastic Process Modeling. In this approach, the load effect is modeled as a stochastic process. Informally defined, a stochastic process L(t) is a random variable that is a function of time t. In this case, the instantaneous value of the load at a point in time t is of interest. Therefore, the time duration aspect is not present in the modeling process. The determination of the probability of failure in a time period from the probability of failure in a point in time can be arithmetically difficult. This method is not suitable for structural life assessment based on reliability theory.
2. Extreme Value Modeling. The statistical characteristics of the extreme load in a time period t can be determined using the basic concepts of extreme statistics. Then, the resulting extreme value probability distribution can be used in the reliability assessment methodology to determine the probability of failure. By varying the time period t from zero to the design structural life, a plot of the probability of failure as a function of time can be developed. This method can be used in reliability and structural life expectancy assessment according to certain failure modes, for example, plate plastic deformation, member buckling, etc.
3. Cumulative Value Modeling. For certain failure modes, e.g., fatigue and brittle fracture, the failure event occur because of the accumulation of damage due to repeated applications of load of variable amplitudes with varying frequencies. The variable amplitude and frequency loading that causes failure can be transformed into an equivalent constant amplitude loading necessary to cause failure. The number of load cycles to failure can be related to the number of years of structural service. Therefore, the cumulative value loading and resulting probability of failure are functions of the number of load applications, which means that they are functions of time.

The time dependence of the loading can come from a number of sources. For the fatigue failure mode, the time dependence is obvious. for the plate plastic deformation failure mode, the time dependence results from increased exposure to extreme events over longer time periods. Another contributing factor could be the general tendency of marine vessels to increase in displacement with age, the result of adding new equipment, carrying more stores and spares than originally planned, and increasing crew size. The resulting load variation with time using one of the above models is shown in Figure 4-1.

4.2.2 Time Dependence of Strength

The strength or resistance R(t) of a structure is also a function of time. Generally, all structural members in boats become weaker in the course of time due to material corrosion, deterioration and sand blasting. The total effect of corrosion, deterioration and sand blasting is referred to, in this study, as plate wastage. The plate wastage allowance is considered and modeled in Section 4.5. Therefore, the structural strength is modeled as a declining amplitude random variable, as shown in Figure 4-1.

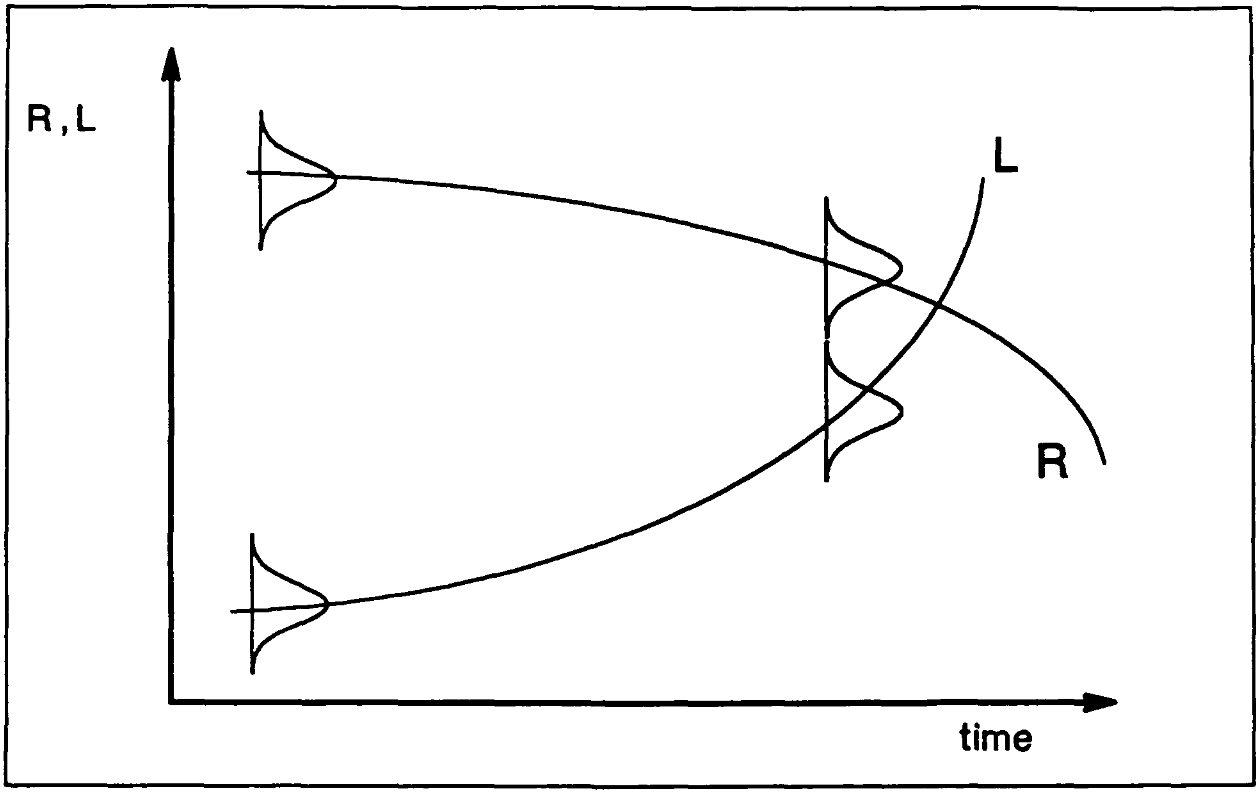

Figure 4-1. Time Dependence of Load Effects and Strength

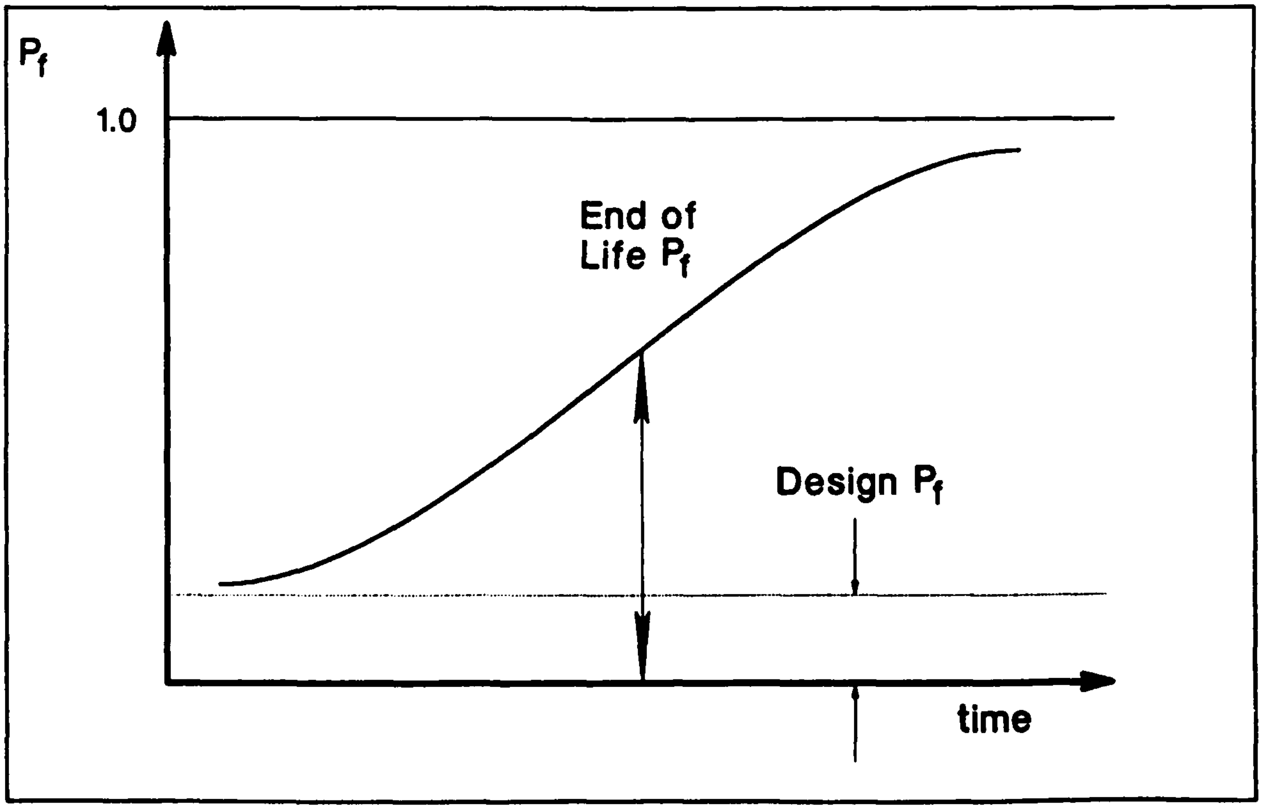

Figure 4-2. Time Dependence of the Probability of Failure

4.2.3 Time Dependence of Risk Measures and Structural Life Definition

Based on the load effect L(t) and structural strength R(t) shown in Figure 4-1, the probability of failure can be computed according to a specified failure mode using, for example, Monte Carlo computer simulation with variance reduction techniques. The resulting probability of failure $P_f(t)$ is a function of time as shown in Figure 4-2. Mathematically, the probability of failure can vary from zero to one. Realistically, the probability of failure varies from an initial (design) probability of failure based on the different design values to a final probability of failure at the end of the useful structural life. The resulting mathematical variation of the probability of failure with time can be viewed as the cumulative distribution function of the structural life SL of a component according to a specified failure mode. Actually, the curve satisfies all the conditions of a cumulative probability distribution function. This relationship can be expressed as follows:

$$F_{SL}(t) = \text{Prob}\ (SL < t) = P_f(t) \tag{4-3}$$

where $F_{SL}(t)$ is the cumulative distribution function of structural life. The density function of structural life $f_{SL}(t)$ can be determined by taking the first derivative of the cumulative distribution function as follows:

$$f_{SL}(t) = \frac{d}{dt} F_{SL}(t) \tag{4-4}$$

The probability density function of structural life can be viewed, based on the basic definition of density functions, as the unconditional probability of failure per unit time, or the unconditional instantaneous probability of failure, or the unconditional failure rate. In contrast, a conditional probability of failure per unit time can be defined. If conditioning is performed on the event "structural survival in the time period (0,t)", the resulting conditional probability of failure is called the hazard function h(t). The hazard function h(t) is a measure of risk (or the probability of failure per unit time) given that the structure did not fail in the time interval (0,t). Therefore, the hazard function plot with time shows the change in risk levels as the structural component becomes older. Mathematically, the hazard function can be related to $f_{SL}(t)$ and $F_{SL}(t)$ as follows:

$$h(t) = \frac{f_{SL}(t)}{1 - F_{SL}(t)} \tag{4-5}$$

For small values of $F_{SL}(t)$, the hazard function is approximately equal to the density function of structural life in numerical values.

Based on the above distributions of structural life, the mean value and variance of structural life can be determined. Confidence levels on the structural life can be determined. The calculations need to be performed for all possible failure modes. Then, the results need to be combined in the final assessment of structural life of the boat system.

4.3 STATISTICS OF EXTREMES

Extreme values based on observational data are very important in structural safety assessment. The prediction of future conditions, especially extreme conditions, are necessary in engineering planning and design. The prediction is performed based on an extrapolation from previously observed data.

Consider a set of observations $(x_1, x_2, \ldots, x_n)$ from identically distributed and independent set of random variables $(X_1, X_2, \ldots, X_n)$. The distribution of X_i is called the initial (or parent) distribution, that has the cumulative probability distribution function $F_X(x)$ and the density probability function $f_X(x)$. The maximum value of the observed values is a random variable M_n which can be represented as

$$M_n = \text{Maximum } (X_1, X_2, \ldots, X_n) \tag{4-6}$$

The exact cumulative and density probability distribution functions of the maximum value are given by, respectively:

$$F_{M_n}(m) = [F_X(m)]^n \tag{4-7}$$

$$f_{M_n}(m) = n[F_X(m)]^{n-1} f_X(m) \tag{4-8}$$

It can be shown that for relatively large values of n, the extreme value distribution approaches an asymptotic form that is not dependent on the exact form of the initial probability distribution; however, it depends on the tail characteristics of the initial distribution in the direction of the extreme. The central portion of the initial distribution has little influence on the asymptotic form of the extreme distribution. These facts are of great practical interest and importance.

For probability distributions of exponential tails, the extreme value probability distribution approaches an extreme value distribution of double exponential form as $n \to \infty$. For example, a normal or lognormal probability distribution approaches a Type I extreme value distribution as $n \to \infty$. In this case, the difference between an exact probability distribution for M_n and the Type I extreme value distribution is relatively small. The difference diminishes as $n \to \infty$. Practically, the difference is negligible for n larger than approximately 25.

For the purpose of the structural life expectancy assessment, the mathematical model for the extreme value probability distribution needs to be a function of n in order to relate the outcome of the analysis of the extreme statistics to time. The extreme value distributions, Type I extreme value distributions, is used in this study to model extreme load effects. Since the mathematical model is not sensitive to the type of the initial distribution, as long as it is within the same general class, the mathematical model used in this study is based on an initial distribution that follows the class of normal probability distributions.

For a normal initial probability distribution of the random variable X with a mean value μ and standard deviation σ, the cumulative distribution function of the largest value M_n of n identically distributed and independent random variables (X_1, X_2, ..., X_n) is given by

$$F_{M_n}(m) = \mathrm{Exp}\{-\mathrm{Exp}[(-\alpha_n/\sigma)(m - \mu - \sigma\, u_n)]\} \tag{4-9}$$

The density function of M_n can be shown to be

$$f_{M_n}(m) = (\alpha_n/\sigma)\ \mathrm{Exp}[-(\alpha_n/\sigma)(m - \mu - \sigma\, u_n)]\ \mathrm{Exp}\{-\mathrm{Exp}[(-\alpha_n/\sigma)(m - \mu - \sigma\, u_n)]\} \tag{4-10}$$

where

$$\alpha_n = [\ 2\ \ln(n)\ ]^{1/2} \tag{4-11}$$

$$u_n = \alpha_n - \{\ \ln[\ln(n)] + \ln(4\pi)\ \}/(2\alpha_n) \tag{4-12}$$

The mean value and standard deviation of M_n can be determined approximately using the central and dispersion characteristics of Type I extreme value distribution, and are given be, respectively:

$$\text{Mean value, } \bar{M}_n = \sigma\, u_n + \mu + \gamma\, \sigma/\alpha_n \tag{4-13}$$

$$\text{Standard Deviation, } SD(M_n) = (\pi/\sqrt{6})(\sigma/\alpha_n) \tag{4-14}$$

The constants π and γ have the values of 3.141593 and 0.577216, respectively.

4.4 OPERATIONAL PROFILE

The operational profile of the patrol boats is defined as the Cartesian product of three boat speeds (Low, Medium and High) and three sea states (Low, Medium and High). The combination of high speed and high sea state was not considered in the study, because the number of hours the boat is operated in this combination is very small. Therefore, there are a total of eight combinations as shown in Tables 4-2 and 4-4. Full-scale trials reported by Purcell, et al(1988) have shown that bottom structure stresses are significantly higher when the boats are operating in head seas than when they are operated at any other heading. This is in agreement with generally accepted design criteria. Therefore, life expectancy evaluation in this study is limited to only head seas.

In order to define the operational profile for the Island-Class patrol boats, a survey was sent out to operators of the boats. The results of the survey are summarized in Tables 4-1 and 4-2. Based on Table 4-1, the

Table 4-1. Annual Operational Profile for the Island-Class Patrol Boat

No.	Name	OPFAC	Total Hours	Case 8 Hours	Comments	Case 8 % Use
1	Monhegan	1305	3101	25		0.81
2	Aquidneck	1309	1864	2		0.11
3	Naushon	1311	1500	3		0.20
4	Sanibel	1312	1200	5		0.42
5	Edisto	1313	1200	10		0.83
6	Sapelo	1314	1000	13		1.30
7	Matinicus	1315	N/A	3	Use Av.Tot.Hrs.	0.14
8	Attu	1317	N/A	10	Use Av.Tot.Hrs.	0.46
10	Chandeleur	1319	N/A	40	Use Av.Tot.Hrs.	1.85
11	Chincoteague	1320	N/A	40	Use Av.Tot.Hrs.	1.85
12	Cushing	1321	N/A	330	Not Considered	
13	Cuttyh ink	1322	N/A	0	Not Considered	
14	Metompkin	1325	N/A	50	Use Av.Tot.Hrs.	2.31
15	Squadron1-1	N/A	2700	40		1.48
16	Squadron1-2	N/A	2700	40		1.48
17	Squadron1-3	N/A	2700	40		1.48
18	Squadron1-4	N/A	2700	40		1.48
19	Squadron2-1	N/A	2500	15		0.60
20	Squadron2-2	N/A	2500	15		0.60
21	Squadron2-3	N/A	2500	15		0.60
	Mean value		2167	23		1.00
	S.D.		714	17		0.66
	COV		0.33	0.73		0.67

Notes: Case 8 refers to High sea state and medium speed
The hours for Case 8 are for all seas

Table 4-2. Operational Profile for the Island-Class Patrol Boat
Head Seas Only

Sea State	Speed		
	Low (12 kts)	Medium (24 kts)	High (29 kts)
Low (1 & 2)	Case #1 4.0 %	Case #2 1.7 %	Case #3 1.0 %
Medium (3 & 4)	Case #4 4.7 %	Case #5 1.3 %	Case #6 0.7 %
High (5)	Case #7 5.3 %	Case #8 1.0 %	Case #9 N A

Table 4-3. Annual Operational Profile for the Cape-Class Patrol Boat

No.	Vessel Name	OPFAC	Number of Hours Per Fiscal Year 1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	No. Yrs.	Mean	S.D.	COV
1	Cross	13121	1377	1852	445	1240	506	735	1124	1018	1467	1261	10	1103	440	0.399
2	George	13107	1472	488	1206	534	1136	1596	1791	1134	1528	945	10	1183	436	0.368
3	Horn	13122	1438	1736	814	327	869	855	1539	1130	1893	1241	10	1184	481	0.406
4	Fairweather	13115	1680	1530	859	946	1036	1115	22				7	1027	537	0.523
5	Starr	13120	1340	1332	778	766	744	760	851	1045			8	952	256	0.269
6	Strait	13109	1325	1612	723	581	86						5	865	608	0.702
7	Current	13108	1876	1628	1760	2374	2819	2330	2766	1654	2090	2051	10	2135	430	0.202
8	Fox	13116	1318	93	1742	1504	1924	2893	1747	2043	1339	2933	10	1754	815	0.465
9	Gull	13105	1857	2130	1325	3277	3098	3124	906	1996	2021	973	10	2071	869	0.42
10	Knox	13113	720	2188	2697	1883	1904	1880	617	1631	1679	1310	10	1651	633	0.383
11	Morgan	13114	1654	943	834	1746	1352	1695	1627	1348	1510	1091	10	1380	327	0.237
12	Shoalwater	13124	520	2511	1846	1766	1646	2224	2568	955	1847	2115	10	1800	646	0.359
13	Upright	13104	2262	2669	2580	2233	1708	2515	1003	1331	1108	1245	10	1865	657	0.352
14	York	13132	1871	2244	299	1619	2058	2767	2080	1319	3449	2038	10	1974	835	0.423
15	Carter	13110	1050	533	431	731	1015	1452	1797	1708	2025	1647	10	1239	563	0.455
16	Hedge	13112	1442	814	701	649	627	650	1216	1325	395		9	869	365	0.42
17	Wash	13111	1225	786	840	885	540	1018	1335	1342	909		9	987	270	0.274
18	Corwin	13126	972	680	1187		1524	1764	2202	1300	1542	1383	9	1395	443	0.317
19	Newagen	13118	647	1070	966	721							4	851	200	0.235
20	Small	13101	1546	782	891	854	859	1535	1598	1466	755		9	1143	377	0.33
21	Coral	13102	1557	834	923	667	398						5	876	430	0.491
22	Henlopen	13128	1152	756	177	817	1533	1498	1780	1170	1493	824	10	1120	482	0.431
23	Jellison	13117	844	1046	1691	1776	1056	2091	1740	879	338		9	1273	481	0.377
24	Romain	13119	1269	1374	1640	1872	2500	1774	1965	1396	1576	1375	10	1674	372	0.222
25	Higgon	13103			575	1143	1782	1027	1571	1070	1250	1314	8	1217	365	0.3
26	Hatteras	13106			2122	1832	2224	2990	2067	1485	1502	1284	8	1938	544	0.281
	No. of Boats		24	24	26	25	25	23	23	22	21	17	230			
	Mean		1351	1318	1156	1310	1398	1752	1561	1352	1510	1472				
	S.D.		421	694	671	714	775	761	627	310	661	535				
	COV		0.31	0.53	0.58	0.55	0.55	0.43	0.40	0.23	0.44	0.36				
	Grand Average		1411 Hours/year													
	Grand S.D.		646.1													
	Grand COV		0.458													

Table 4-4. Operational Profile for the Cape-Class Patrol Boat
Head Seas Only

Sea State	Speed Low (4 kts)	Medium (12 kts)	High (20 kts)
Low (1 & 2)	Case #1 0.8 %	Case #2 6.1 %	Case #3 0.9 %
Medium (3 & 4)	Case #4 1.6 %	Case #5 7.5 %	Case #6 0.7 %
High (5)	Case #7 1.0 %	Case #8 1.4 %	Case #9 N A

percent use of the boats in combination number 8 in all seas is 1%. However, in this study, the operational profile as shown in Table 4-2 is used. According to this table, the percent use of the boats in combination number 8 in head seas is 1%. According to Table 4-1, the annual number of operational hours of the Island-Class patrol boat has a mean value of 2167 hours, a standard deviation of 714 hours and a coefficient of variation (COV) of 0.33. The corresponding statistics for the percent use of the boat in combination 8 are 1%, 0.66% and 0.67. In this study, the annual number of operational hours of the Island-Class patrol boat is assumed to be a random variable with a normal distribution and the mean value and COV as determined above. The normal distribution was selected based on the available results of the operational profile analysis of the Cape-Class patrol boat as discussed at the end of this section. In addition, the percent use in the various sea state-speed combination cells of the operational profile matrix are considered to be random variables. They are also assumed to be normally distributed with statistics found from Table 4-1. The effect of varying these values is considered in the study by performing a parametric analysis as described in Chapter 9.

For the Heritage-Class patrol boat, the operational profile characteristics are assumed to be the same as for the Island-Class patrol boat.

The operational profile of the Cape-Class patrol boats was defined based on an analysis of actual operational history of the boats. The results of the analysis are summarized in Tables 4-3 and 4-4. Based on Table 4-3, the percent use of the boats in combination number 8 in all seas is 1.4%. However, in this study, the operational profile as shown in Table 4-4 is used. According to this table, the percent use of the boats in combination number 8 in head seas is 1.4%. According to Table 4-3, the annual number of hours of operation of the Cape-Class patrol boat has a mean value of 1410 hours, a standard deviation of 646 hours and a coefficient of variation (COV) of 0.45. In this study, the annual number of hours of operation of the Cape-Class patrol boat is also considered to be a random variable. The total annual hours, as reported in Table 4-3, are plotted in the form of a histogram in Figure 4-3. A statistical goodness-of-fit test indicated that a normal probability distribution with the above statistics can be assumed. Because the Cape-Class evaluation is being used to calibrate the analytical model, a parametric analysis was not performed on this class of boats.

4.5 PLATE WASTAGE ALLOWANCE

The types of steel used and that which will be used in the construction of the Island, Heritage and Cape-Class patrol boats are BS4360 type 43A, ASTM A572 high strength low alloy, and A36 Galvanized steel. These are very common types of steel that are used for many years in the construction of marine structures. Steels are selected for marine service because of such factors as availability, cost, ease of fabrication, design experience, and physical and mechanical properties.

The patrol boats that are owned and operated by the U.S. Coast Guard are usually inspected and maintained every two years. As part of the

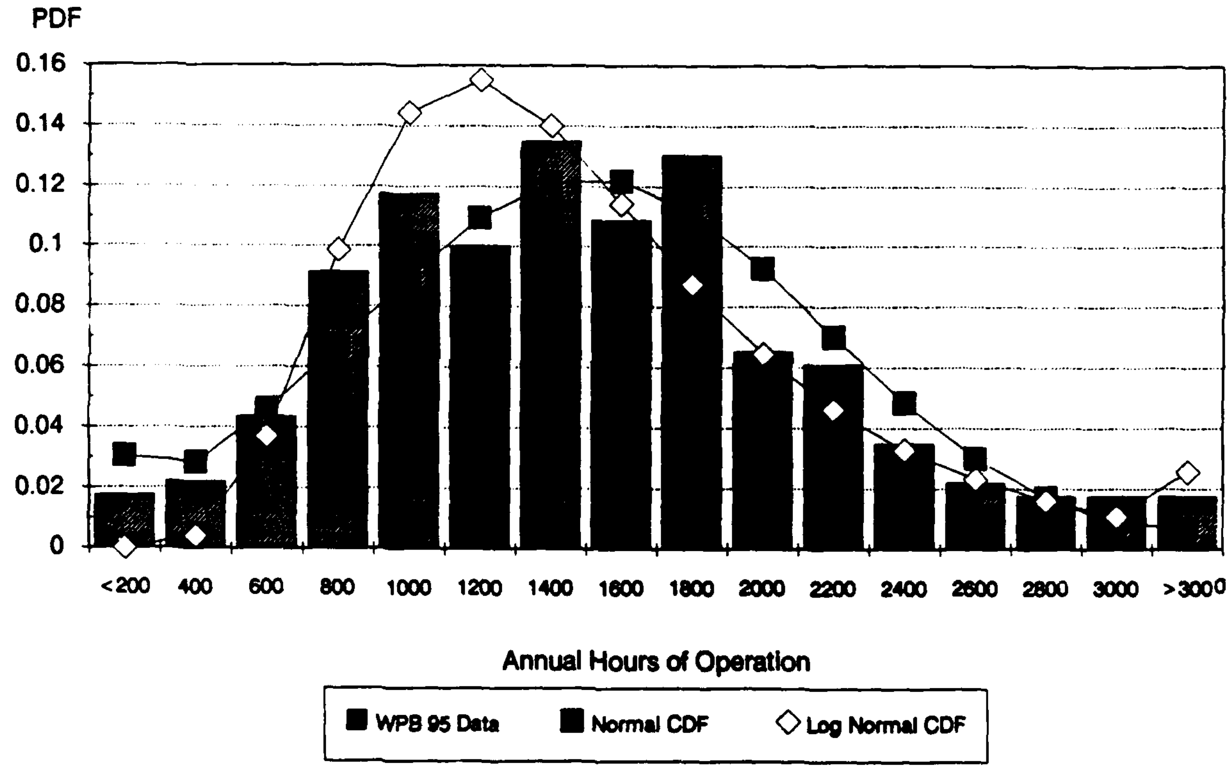

Figure 4-3. Probability Distribution for WPB 95 Operational Profile

maintenance procedure, a boat is inspected for corrosion occurrence. Any observed corrosion which is considered excessive is repaired. In addition, the outside surface of the boat's hull is sandblasted in order to remove any corrosion, bio-fouling, and loose metal and paint. The boat is then repainted. Based on this process, it is obvious that the thickness of the plating of the boat reduces with time. In this report the reduction is called the wastage, and it consists of two components, corrosion and sandblasting wastage.

4.5.1 Corrosion Wastage

The corrosion-related behavior of steel in a marine environment shows striking differences in various exposure zones including geographic location and exposure type (atmospheric, tidal, or total immersion). Other factors that affect the rate of corrosion include the type of steel, carbon content, alloys, residual elements in the steel such as copper, nickel, silicon, level of chloride ion, electrical conductivity of steel, oxygen level, water velocity, temperature, bio-fouling, stress, pollution, silt and suspended sediments, film formation, the condition of the exposed surface, and coating and paint types, etc. The steel corrosion in a marine environment takes two forms, either an average reduction in thickness, or pitting or both. A detailed discussion and analysis of these factors is available in the Seawater Corrosion Handbook (Schumacher, 1979).

For patrol boats, inside as well as outside corrosion is of concern. Based on the inspection records of the Island-Class patrol boats, inside corrosion of the plating was not reported. However, based on these records, slight corrosion, mostly in the form pitting, was reported on the outside surface. This good performance is attributed mainly to the special coating and paint provided on the outside surface of the boat's hulls. Similar performance can be assumed for the Heritage-Class patrol boats. For the Cape-Class patrol boats, galvanized A36 steel was used. For this type of steel, no corrosion was assumed. Therefore, the corrosion allowance for these three boat classes is assumed to be negligible, and steel wastage of the plating is mainly due to the sandblasting every other year.

4.5.2 Sandblasting Wastage

According to current practices of the U.S. Coast Guard, once every two years the outside surface of a boat's hull is sandblasted in order to remove any corrosion, bio-fouling, loose metal and old paint, and then is repainted. This process and the slight corrosion results in a reduction in the plate thickness. The reduction is on the order of about one to three mils per year (mpy).

Based on the literature review (Schumacher, 1979), the plate wastage rate is assumed to have a mean value in the range of one to three mpy, COV of 0.1 to 0.25 and a Lognormal distribution type. Furthermore, the rate of corrosion is assumed to be stationary in time, i.e., its mean value, COV and distribution type are independent of time. The effect of this assumption on the expected life of the boats will be investigated in Chapter 9.

4.5.3 The Wastage Allowance Model

For a wastage rate that has a mean value of R_m, a standard deviation of σ_R and a coefficient of variation of COV(R), the wastage at the end of any year t is given by

$$\text{mean value, } W_t = t\, R_m \tag{4-15}$$

$$\text{coefficient of variation, } COV(W_t) = [t^2\, COV(R)^2]^{1/2} \tag{4-16}$$

in which W_t is the wastage at time t. Therefore, based on this model, the mean value of wastage is linearly increasing with time, and the uncertainty, i.e., COV, is increasing with time. This behavior is graphically represented in Figure 4-4a.

In order to make the wastage model compatible with the extreme value modeling of the load, it needs further development. According to the extreme value modeling, an extreme load is evaluated in a time period T, where T can be any value from zero to the design life of a boat. This extreme load can occur at any point in time t within the time period T. On the other hand, the plate wastage is a non-stationary stochastic process within the same time period T. This stochastic process can be simulated using Monte Carlo methods and converted into a random variable. The process can be summarized as follows:

1. Specify a wastage rate R in the form of a mean value and COV. The distribution type can be taken as Lognormal in order not to have any negative values for the rate.
2. Set the time period T to an initial value larger than zero. The wastage at zero time period is zero.
3. Randomly generate time according to a uniform probability distribution of the time period T.
4. At the generated time t, evaluated the statistics of wastage according to equations 4-15 and 4-16. The distribution type is Lognormal.
5. Randomly generate M wastage values according to the distribution as defined in step 3.
6. Repeat steps 2 to 4 N times.
7. Determine the mean value, COV and distribution type for the resulting M times N values of the wastage allowance W_a in the time period T as set in step 1.
8. Go to step 1, and increase the value of T, and repeat steps 2 to 5 for the new T value.

The resulting wastage allowance random variable W_a is a function of the time period T as shown in Figure 4-4b. The simulation processes as described in these steps was performed for wastage rates R_m of 1, 2 and 3 mpy, COV(R) of 0.1, 0.25 and 0.4 and time periods T of 1, 5, 10, 15, 20, 25 and 30 years. Based on this parametric analysis, it can be concluded that the mean value of wastage allowance is dependent on the wastage rate and the period T, and is not dependent on the COV(R); while COV of wastage allowance is dependent on COV(R) and the time period, and is not dependent on the wastage rate R. These results were plotted in Figures 4-5, 4-6 and 4-7. Figure 4-5 shows the mean value of wastage allowance as a function of

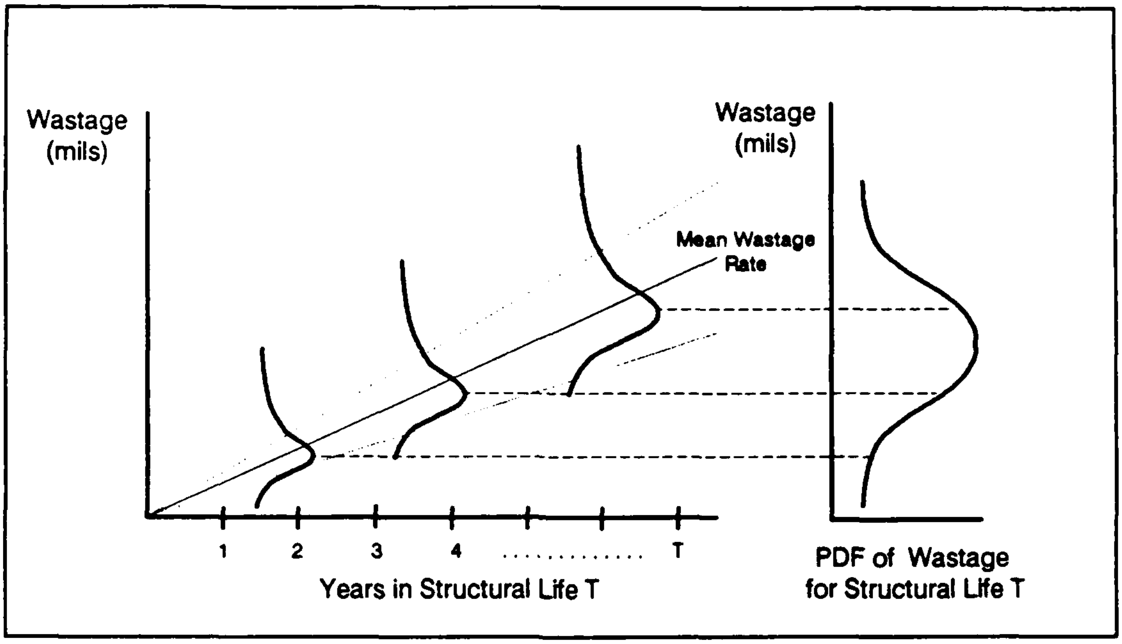

Figure 4-4a. Wastage as a Function of Time

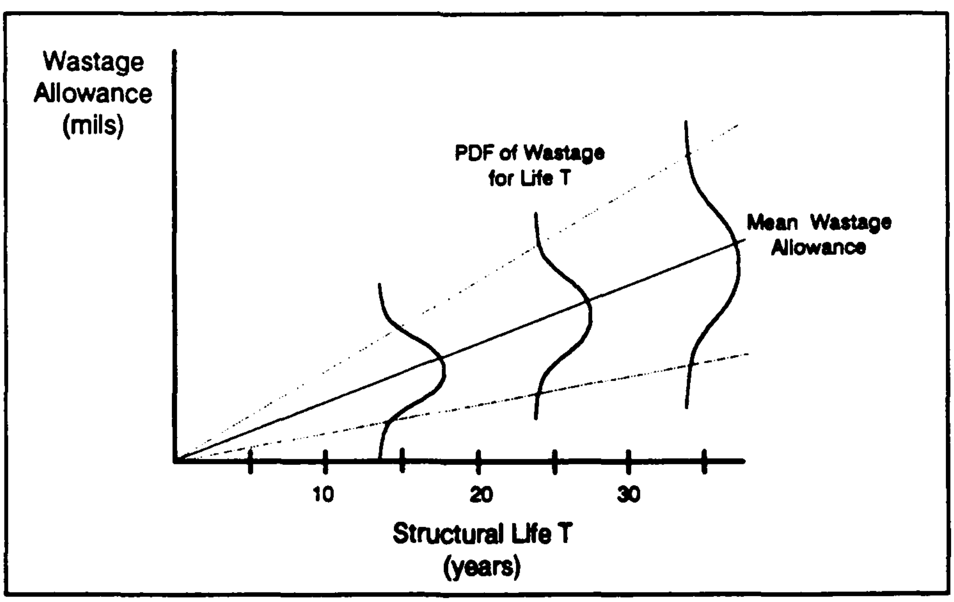

Figure 4-4b. Wastage Allowance as a Function of Time

time for three wastage rates. Figure 4-6 shows the mean value of wastage allowance as a function of time for three COV's of the wastage rate. Figure 4-7 shows the COV of wastage allowance as a function of time and COV(R).

Using the conclusions of the parametric analysis, regression analyses were performed to determine prediction models for the mean value and COV of wastage allowance. The mean value of wastage was considered as a function of the wastage rate R_m and the time period T, while the COV of wastage allowance was considered as a function of COV(R) and the time period T. Two models were investigated, the linear and the product models. The selected prediction model for the mean value of the wastage allowance is given by

$$\text{Mean Value, } W_a = 0.926733\, R_m\, T^{(0.8082)} \tag{4-17}$$

The standard statistical error for this model is 0.08619, the R^2 value is 0.993315 and the mean absolute relative error is 0.0653137. Statistically, this is considered to be an excellent prediction model. The prediction selected model for the COV of the wastage allowance is given by

$$COV(W_a) = 0.41305\, [COV(R)]^{(0.2864)}\, T^{(0.29933)} \tag{4-18}$$

The standard statistical error for this model is 0.63657, the R^2 value is 0.6353 and the mean absolute relative error is 0.17567. Statistically, this is considered to be a good prediction model. These models are used as part of the reliability-based structural life expectancy methodology.

In order to determine the distribution type for the wastage allowance, two cases were considered. In the first case, the mean value and COV of the wastage rate were taken to be 3 mpy and 0.1, respectively, and the time period equals to 10 years. The wastage allowance was simulated 2000 times, and a distribution goodness-of-fit was performed. The results are shown in Figure 4-8. In the second case, the mean value and COV of the wastage rate were taken to be 3 mpy and 0.25, respectively, and the time period equals to 25 years. The wastage allowance was simulated 2000 times, and a distribution goodness-of-fit was performed. The results are shown in Figure 4-9. Based on these two cases, it can be concluded that the wastage allowance can be considered to follow a normal probability distribution with non-negative values, i.e., any simulated negative value for wastage allowance is replaced by a zero wastage allowance. This results in a heavier lower tail consistent with the actual distribution, resulting in reducing the statistical error in the assumed normal probability distribution model.

4.6 SUMMARY OF METHODOLOGY

The proposed methodology consists of several logical components. These components and their interaction and inter-dependence are shown in Figure 4-10.

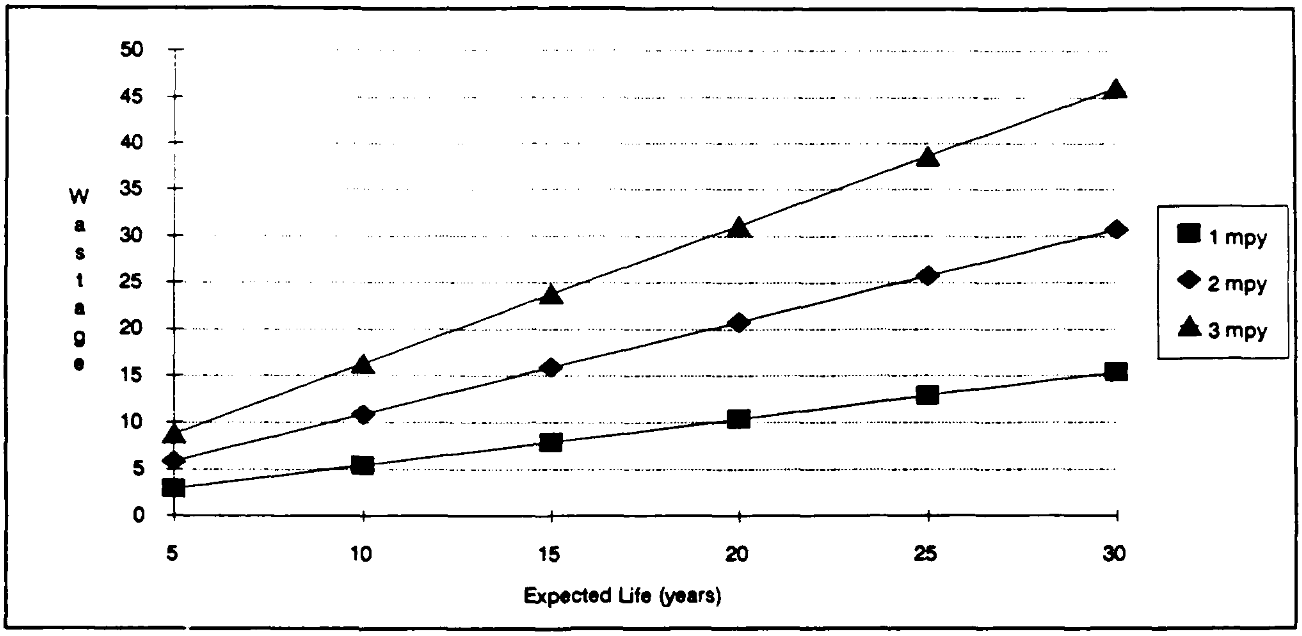

Figure 4-5. Mean Value of Wastage Allowance as a Function of T and R_m

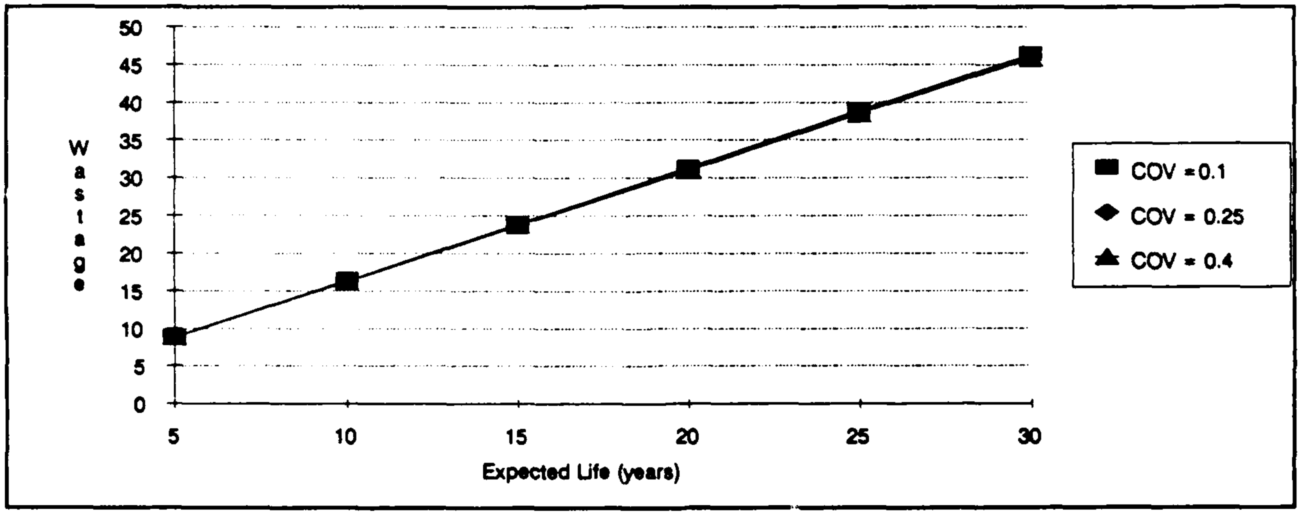

Figure 4-6. Mean Value of Wastage Allowance as a Function of T and COV(R)

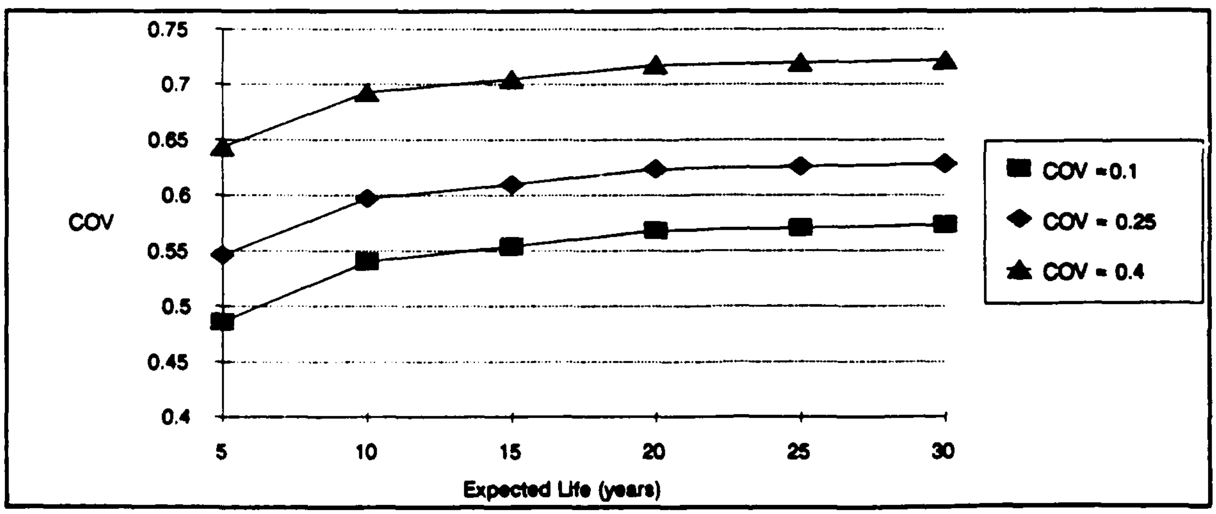

Figure 4-7. COV of Wastage Allowance as a Function of T and COV(R)

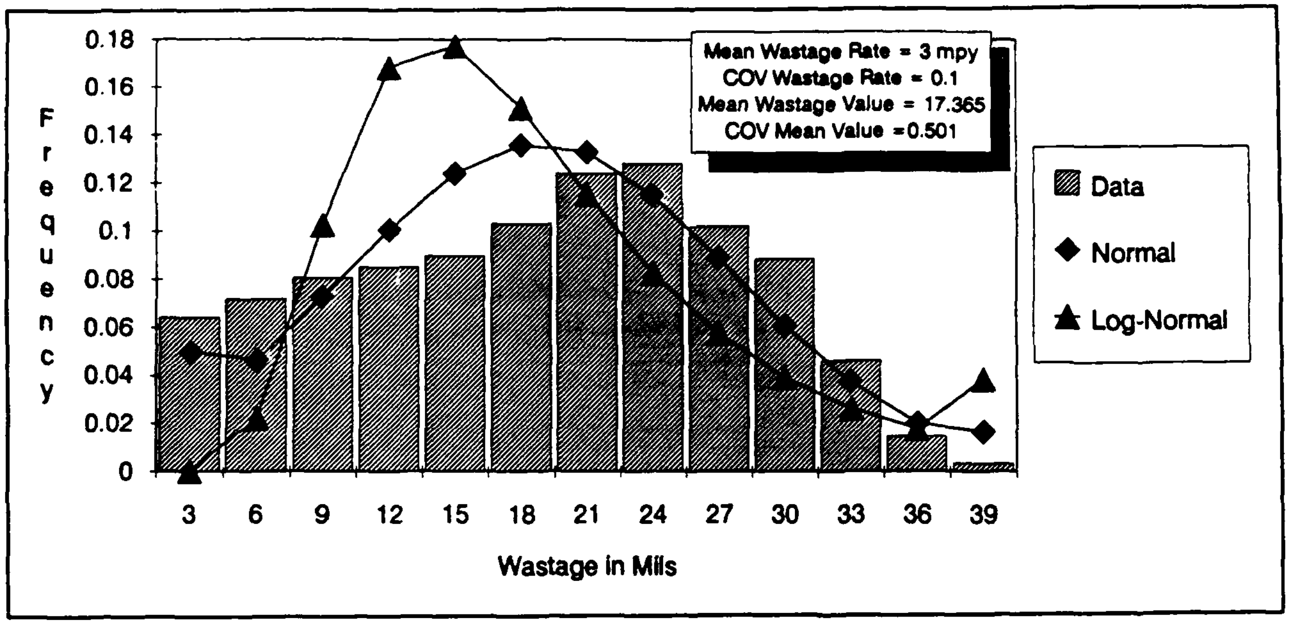

Figure 4-8. Wastage Allowance Probability Density Function for an Expected Life of 10 Years

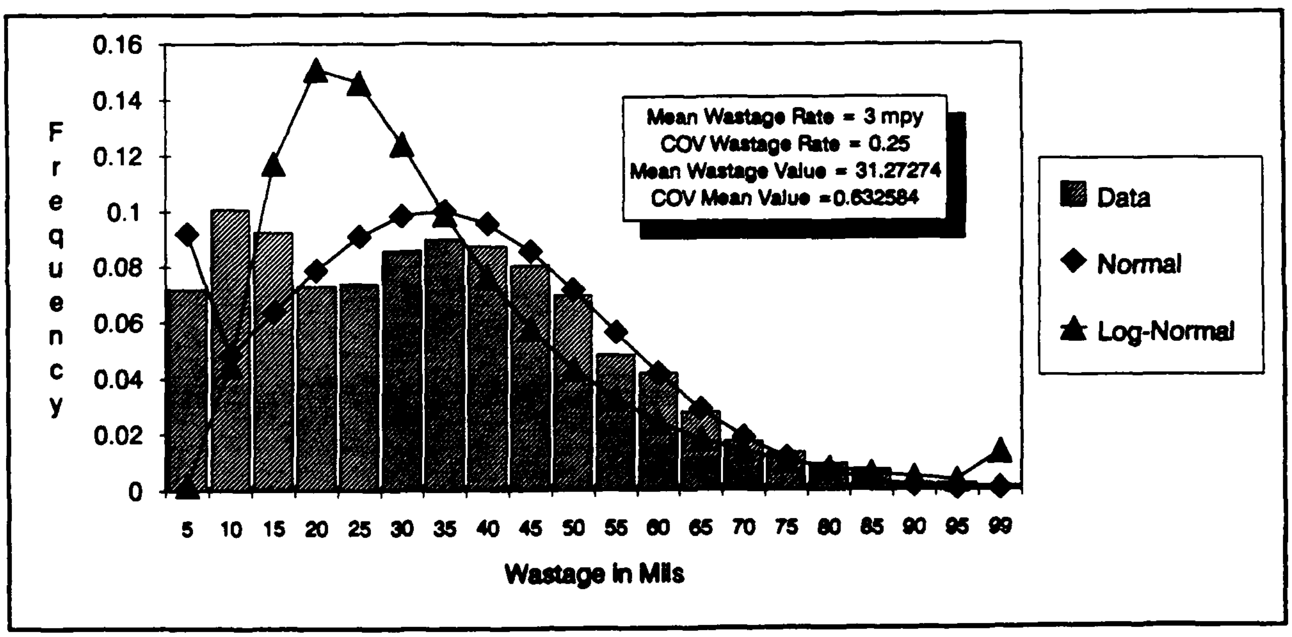

Figure 4-9. Wastage Allowance Probability Density Function for an Expected Life of 25 Years

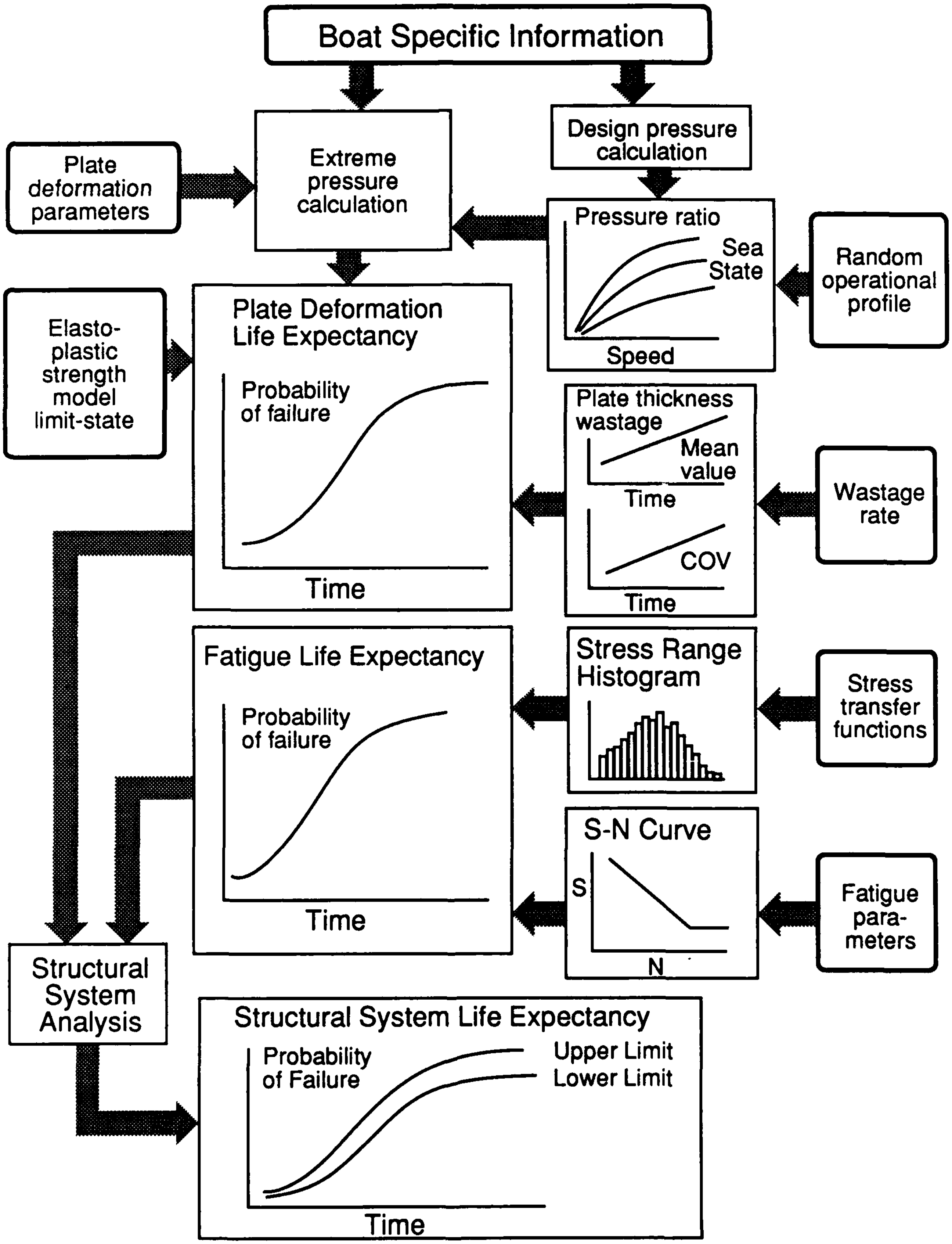

FIGURE 4-10 The Life Assessment Methodology

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5. STRUCTURAL LIFE ASSESSMENT OF COMPONENTS

5.1 PLASTIC PLATE DEFORMATION

The structural life of a boat according to the plate deformation failure mode can be determined in several steps that are discussed in the following sections.

5.1.1 Limit State Equation

The limit state equation for the local plate deformation failure mode can be expressed in a general form as

$$g(X) = R(X_1, X_2, \ldots, X_{n-m}) - L(X_{n-m+1}, \ldots, X_n) \tag{5-1}$$

in which $R(X_1, X_2, \ldots, X_{n-m})$ is the strength of the structural component or system according to the specified failure mode, $X_1, X_2, \ldots, X_{n-m}$ are the basic strength random variables, $L(X_{n-m+1}, \ldots, X_n)$ is the load effect on the structural component or system in the specified failure mode, and $X_{n-m+1}, \ldots, X_n$ are the basic load variables. Since $X_1, \ldots, X_n$ are random variables, therefore, $g(X)$ is a random variable. In this study, the limit state equation for plate yielding is given by

$$g(X) = \text{Resistance} - \text{Still Water Load} - \text{Dynamic Load} \tag{5-2}$$

Each of the terms in the above equation are expressed in units of pressure. The still water load is the hydrostatic pressure at the depth of the critical region. The dynamic pressure is the extreme dynamic pressure in a time period T. The resistance term is an empirical expression as developed by Hughes (1981) based on elasto-plastic methods and is given as:

$$\text{Resistance} = \frac{F_Y^2}{E} \{Q_Y + T(R_w)[\Delta Q_0 + \Delta Q_1 R_w]\} \tag{5-3}$$

where

- F_Y - is the yield stress of the material
- E - is the modulus of elasticity of the material
- Q_Y - is the initial yield load calculated from elastic theory
- ΔQ_0 - accounts for curved transition portion of load deflection curve (see Figure 5-1)
- ΔQ_1 - accounts for subsequent straight portion of load deflection curve
- R_w - ratio of the deflection w_p at a given loading to the deflection at the completion of the edge hinge formation w_{p0}.

$$T(R_w) = [1 - (1-R_w)^3]^{1/3} \quad \text{for } R_w \le 1$$
$$= 1 \quad \text{for } R_w > 1$$

This expression was calibrated with available experimental data (Hughes, 1981). It was found to be extremely accurate for w_p/t_h ratios less than 4. As the w_p/t_h ratios increase beyond 4 the accuracy decreases

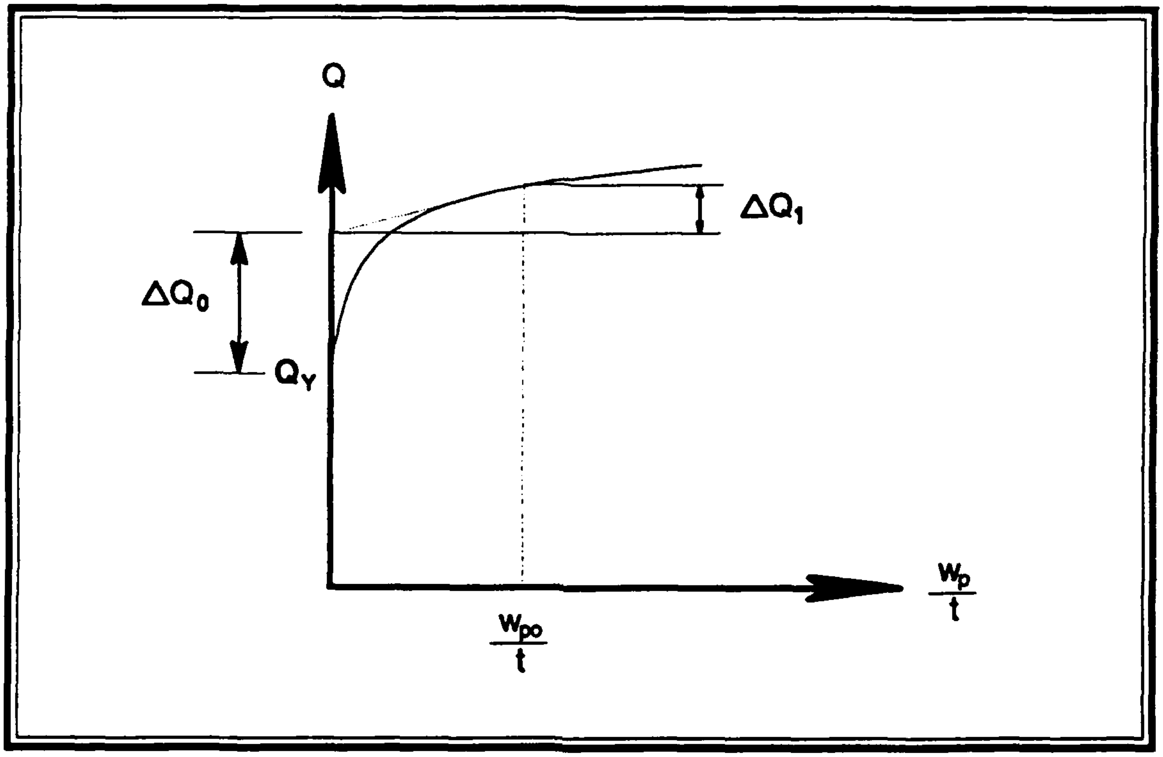

Figure 5-1. Load vs. Permanent Set for Plates of Finite Aspect Ratio (Hughes, 1981)

for plates of low aspect ratio, but remains quite good for plates with aspect ratios above 2.0.

5.1.2 Still-Water Pressure

Because the stresses due to still-water pressure for the Island-Class patrol boat were not measured, the mean value of the still-water pressure was determined based on a hydrostatic analysis and was found to be 2.667 psi (Ayyub and White, 1987). The coefficient of variation and distribution type of still-water pressure are assumed to be 0.20 and normal, respectively (after White and Ayyub, 1985).

The still-water pressures for the Heritage and Cape-Class patrol boats were determined by assuming the boats float at their design waterlines at full load displacement. The draft to the bottom plating in the critical region was used to determine the pressure. For both the Heritage and Cape-Class boats that draft was found to be 4.5 feet, resulting in a still-water pressure of 2 psi. The coefficient of variation and distribution type of the still-water pressure were assumed to be the same as that used for the Island-Class.

The total pressure applied to the plate is the still-water pressure plus the extreme dynamic pressure. The calculation of the extreme dynamic pressure is presented in section 5.1.4

5.1.3 Design Dynamic Pressures

In this study, only loads and load effects in head seas are considered. No other headings are considered because their stress records (1988) indicate that they result in much smaller stresses than the head seas condition. These findings are according to tests and stress measurements at the locations of interest for the Island-Class patrol boat as reported by Purcell, et al (1988). Eight combinations of ship speed and sea state for the head seas condition are considered as described in Tables 4-2 and 4-4. The combination of high sea state and high speed was not considered because historical records indicate that these types of boats are almost never operated under those conditions.

In order to facilitate a consistent comparison between the vessels involved in this study, a means of determining the statistics of the loading needs to be developed. Earlier work with the Island-Class (Ayyub and White 1987, 1988) had resulted in a methodology for describing the lifetime loading of the boat based on full-scale measurements. Since these measurements represent the best available data, it was determined that they and the methodology for the statistical description of the loading would be used in this study.

The methodology used by Ayyub and White (1988) was based on a mean maximum pressure from the collected data to determine the lifetime extreme value distribution for the loading. In order to use this approach again, a means of relating the mean maximum pressure found for the Island-Class to a similar pressure for the other two boats was needed. One way of developing this relationship would be to calculate the design dynamic pressure for the Island-Class patrol boat in each combination and compare it with the mean

maximum pressure for the Island-Class. The ratio of these pressures would then be used to determine the mean maximum pressures for each of the other two boats based on their calculated design dynamic pressures.

The calculation of the design dynamic pressures is in accordance with conventional practices of the U.S. Coast Guard. The pressure calculations for planning boats is based on the classic paper by Heller and Jasper (1960) and the work done at Davidson Laboratory by Fridsma (1971) and later Savitsky (1964, 1976). Essentially, the calculation of the design dynamic pressure consists of the following:

$$P_D = (F_L \; F \; P_I) + P_S \tag{5-4}$$

where

- P_D = Total design pressure
- F_L = Longitudinal load distribution factor, from Heller and Jasper (1960). For the area of interest, it is equal to 1.0.
- F = Area distribution factor taken from Spencer (1975).
- P_I = Impact pressure from Heller and Jasper (1960).
- P_S = Hydrostatic pressure for vessel at full load waterline, ρgd.
- d = Full load draft, in feet.
- g = Acceleration of gravity in feet/Sec^2
- ρ = Water density.

The first term in equation (5-4) can be considered as the design *dynamic* pressure. It is an equivalent uniform pressure over a plate panel area caused by the motions of the boat at a specified condition of speed and sea state. The impact pressure term comes from Heller and Jasper (1960) in a form expressed by Silvia (1978) and can be written as

$$P_I = \frac{\Delta_{\#} \cos \beta}{14.55 \; L_{WL} \; B_x} \left(1 + N_{1/10CG}\right) \tag{5-5}$$

where

- $\Delta_{\#}$ = Full load displacement in pounds.
- β = Deadrise angle at station 5, representing the average angle.
- L_{WL} = Length on the full load waterline at rest.
- B_x = Maximum chine beam.

The $N_{1/10CG}$ enclosed in the parentheses in equation (5-5) is the average of the highest 1/10 accelerations of the center of gravity of the boat operating under specified conditions of loading, sea state and speed. An expression for approximating this value in cases where model test data is not available was presented by Hoggard and Jones in (1980). Their equation, given below, was based on a regression analysis of the existing model and full-scale test data.

$$N_{1/10CG} = 7.0 \left(\frac{H_{1/3}}{B_x}\right) \left(\frac{V}{(g\nabla^{1/3})^{1/2}}\right) \left(1 + \frac{\tau}{2}\right)^{0.25} \left(\frac{L_p}{B_x}\right)^{-1.25} \tag{5-6}$$

where

$H_{1/3}$	=	Significant wave height for the given sea state.
v	=	Boat velocity in feet per second.
∇	=	Volumetric displacement in cubic feet.
g	=	Acceleration of gravity, taken as 32.174 ft/sec^2.
τ	=	Smooth water running trim angle, taken as 2° for all boats in this study.
L_p	=	Projected chine length.

It is worth discussing the notion of projected chine length, L_p, at this point. Hoggard and Jones use projected chine length in the last term of equation (5-6). That term is a length-to-beam ratio and is a means of representing planing area. The original work by Fridsma (1967) also used length-to-beam ratio to represent planing area, but in that work all of the models were parametric variations of the same hard-chine hull. Since the beam was constant, varying the length-to-beam ratio was in fact varying the planing area. It seems apparent that Hoggard and Jones introduced the concept of projected chine length in an attempt to find a measurable length that would consistently define the planing area when used with the maximum chine beam, B_x. Because all of the boats in their study had hard-chine hulls, this idea is workable. However, because the same type of information doesn't exist for round-bilge semi-displacement boats, equation (5-6) is being used to determine the accelerations for those boats. Engineers tend to measure the projected chine length on round-bilge hulls on the basis of not including the rounded bilge length. This approach is not consistent with the intent of Fridsma. Using a shorter L_p in equation (5-6) gives significantly higher accelerations at all speeds. That does not make sense in view of the known performance of round-bilge hulls. Those hulls generally provide much easier motions (and lower accelerations) at low speeds and about the same motions at high speeds as do hard-chine planing hulls. The penalty for rounding the bilge comes in powering performance. It is believed that when using equation (5-6) for round-bilge hulls, the waterline length, L_{WL}, should be used in place of projected chine length, L_p. For the Island-Class hull, using L_{WL} in equation (5-6) gives accelerations which are in agreement with those reported by Davidson Laboratory (1987) for the model tests of the Island-Class.

The area distribution factor, F, in equation (5-4) is taken from the work done by Spencer (1975). His suggested model relates the maximum design impact pressure, which is extremely localized, to a uniform design pressure on the plate panels between stiffeners. His work was done for aluminum crewboats, but has been adopted by the U.S. Coast Guard for use in planing boat design. The area distribution factor can be evaluated as follows:

$$F = 0.1 + \frac{1}{(8.1A^2 + 15.6A + 1.1)} \qquad (5\text{-}7)$$

where

A is the panel area ratio, given as:

$$A = \frac{\text{(panel area)}}{(25\Delta/d)}$$

The final factor in equation (5-4) is the longitudinal distribution factor, F_L. This factor was first shown in Heller and Jasper's work (1960) and was meant to account for the variation of peak impact pressure along the length of the boat. The factor is equal to 1.0 for the length between 25% to 50% of the L_{WL}. As this is the area of interest in this report, the factor is considered to be equal to 1.0.

The approach described above to calculate design pressures for the Island Class boat is realistic because the calculated accelerations are in agreement with both model and field test results. The Cape Class, however, for its displacement, is relatively underpowered to be considered a "planing boat" in the sense that Fridsma and Savitsky described. Some of their key parameters for calculating the design pressures for the Cape Class lie outside the range of the model test data, and are extrapolations in the regression equations. In addition, the Island Class is a round-bilge boat with deadrise angles that vary dramatically along the length. The models used in almost all of the testing done by Fridsma were prismatic hull forms. However, because the procedure is the best available to date, it has been accepted as common practice in the design of patrol boats. Even if the Island and Cape classes are not planing boats, they can slam in certain seas. It is this slamming pressure which needs to be estimated, and its effect on the hull structure should be considered. The approach described above provides a reasonable means of estimating a design value for slamming pressure.

Tables 5-1, 5-2, and 5-3 provide summaries of the design pressure calculations for the Island, Heritage, and Cape classes, respectively.

5.1.4 Design to Maximum Dynamic Pressure Ratios

The yielding of the bottom plating of a boat can be expressed by the following equation (Hughes, 1983):

$$\nabla^4 w = \frac{1}{\Delta}\left[p + N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy}\frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial x^2} \right] \qquad (5\text{-}8)$$

where

- $\nabla^4 w$ - the Bi-Harmonic equation
- w - plate deflection in the z direction
- p - uniform lateral pressure
- D - the plate flexural rigidity, given by
  $$= \frac{E\, t_h^{3}}{12(1-\nu^2)}$$
- E - the modulus of elasticity

Table 5-1. Design Pressures for the Island-Class Patrol Boat

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Initial Design Data								
Significant Wave Height (ft)	3	3	3	8	8	7	10	10
Speed (kts)	12	24	29	12	24	29	12	24
Smooth Water Running Trim	2	2	2	2	2	2	2	2
Length of Waterline (ft)	104	104	104	104	104	104	104	104
Proj Chine Length (ft)	104	104	104	104	104	104	104	104
Max Chine Beam (ft)	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5
Displacement (LT)	165.12	165.12	165.12	165.12	165.12	165.12	165.12	165.12
Draft (ft)	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48
Deadrise Angle	12	12	12	12	12	12	12	12
Plate Panel Length (in)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
Plate Panel Width (in)	11.75	11.75	11.75	11.75	11.75	11.75	11.75	11.75
Calculations								
Highest 1/10 Accel at CG	0.133	0.266	0.322	0.355	0.710	0.751	0.444	0.888
Spencer Reference Area	637.037	637.037	637.037	637.037	637.037	637.037	637.037	637.037
Plate Panel Area	1.918	1.918	1.918	1.918	1.918	1.918	1.918	1.918
Area Ratio, A	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Area Distribution Factor, F	0.972	0.972	0.972	0.972	0.972	0.972	0.972	0.972
Design Dynamic Pressure	13.502	15.090	15.751	16.148	20.380	20.865	17.206	22.496
Still Water Pressure	2.667	2.667	2.667	2.667	2.667	2.667	2.667	2.667
Total Design Pressure	16.169	17.757	18.418	18.815	23.047	23.532	19.873	25.163

Table 5-2. Design Pressures for the Heritage-Class Patrol Boat

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Initial Design Data								
Significant Wave Height (ft)	3	3	3	8	8	7	10	10
Speed (kts)	12	24	29	12	24	29	12	24
Smooth Water Running Trim	2	2	2	2	2	2	2	2
Length of Waterline (ft)	110	110	110	110	110	110	110	110
Proj Chine Length (ft)	110	110	110	110	110	110	110	110
Max Chine Beam (ft)	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8
Displacement (LT)	161.8	161.8	161.8	161.8	161.8	161.8	161.8	161.8
Draft (ft)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Deadrise Angle	19	19	19	19	19	19	19	19
Plate Panel Length (in)	42	42	42	42	42	42	42	42
Plate Panel Width (in)	12	12	12	12	12	12	12	12
Calculations								
Highest 1/10 Accel at CG	0.127	0.253	0.306	0.338	0.675	0.714	0.422	0.844
Spencer Reference Area	898.889	898.889	898.889	898.889	898.889	898.889	898.889	898.889
Plate Panel Area	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
Area Ratio, A	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Area Distribution Factor, F	0.961	0.961	0.961	0.961	0.961	0.961	0.961	0.961
Design Dynamic Pressure	11.150	12.403	12.925	13.239	16.581	16.964	14.074	18.252
Still Water Pressure	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Total Design Pressure	13.150	14.403	14.925	15.239	18.581	18.964	16.074	20.252

Table 5-3. Design Pressures for the Cape-Class Patrol Boat

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Initial Design Data								
Significant Wave Height (ft)	3	3	3	8	8	7	10	10
Speed (kts)	12	24	29	12	24	29	12	24
Smooth Water Running Trim	2	2	2	2	2	2	2	2
Length of Waterline (ft)	90	90	90	90	90	90	90	90
Proj Chine Length (ft)	90	90	90	90	90	90	90	90
Max Chine Beam (ft)	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
Displacement (LT)	105	105	105	105	105	105	105	105
Draft (ft)	6	6	6	6	6	6	6	6
Deadrise Angle	15	15	15	15	15	15	15	15
Plate Panel Length (in)	72	72	72	72	72	72	72	72
Plate Panel Width (in)	18	18	18	18	18	18	18	18
Calculations								
Highest 1/10 Accel at CG	0.170	0.340	0.410	0.453	0.906	0.958	0.566	1.132
Spencer Reference Area	437.500	437.500	437.500	437.500	437.500	437.500	437.500	437.500
Plate Panel Area	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000
Area Ratio, A	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
Area Distribution Factor, F	0.802	0.802	0.802	0.802	0.802	0.802	0.802	0.802
Design Dynamic Pressure	8.799	10.077	10.609	10.929	14.335	14.726	11.780	16.039
Still Water Pressure	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Total Design Pressure	10.799	12.077	12.609	12.929	16.335	16.726	13.780	18.039

t_h - the thickness of the plate
ν - Poisson ratio
N_x - the in-plane force on the plate in the x direction
N_y - the in-plane force on the plate in the y direction
N_{xy} - the in-plane shearing force

Except in cases where the inplane forces are explicitly known, there are not many closed form solutions to this equation. In ship structures, the principle application of equation (5-8) is in the case of plating subjected to a large compressive in-plane stress N_x , which brings with it the possibility of plate buckling. However, the case of interest in this study presents a possibility of both compressive and tensile in-plane forces. Mansour (1967) presented a numerical solution to this equation for both compressive and tensile forces N_x. A description of this solution, the boundary conditions established, and the development of the load effect terms are provided by Ayyub and White (1987).

The loads on the panel of plating can be generally divided into those resulting from hydrostatics in still-water, and those which are results of the boat's speed and motion. An algebraic manipulation of Mansour's solution of equation (5-8) into the form of the *Von Mises* yield stress criteria allows the load effect terms to be expressed as follows (Ayyub and White, 1987):

$$L^2 = \left(\frac{N_x^{\,2}}{t_h^{\,2}} + 36p^2k^* \frac{b^2}{t_h^{\,4}} + 6N_x pk^{**} \frac{b^2}{t_h^{\,3}} \right) + \left(72pk^*\Delta p \frac{b^4}{t_h^{\,4}} + 6N_x \Delta pk^{**} \frac{b^2}{t_h^{\,3}} \right) + \left(36\Delta p^2 k^* \frac{b^4}{t_h^{\,4}} \right) \tag{5-9}$$

where

L - the maximum total combined stress at the center of the plate
N_x - still-water in-plane load
p - still-water hydrostatic pressure
t_h - plate thickness
b - width of the plate (athwartship dimension)
Δp - Effective dynamic pressure
k^*, k^{**} - algebraic combinations of Mansour's dimensionless coefficients β and γ

The first term in equation (5-9) represents the contribution due to the still-water condition, the third term represents the contribution of the dynamic effects, and the middle term is an interaction term resulting from the *Von Mises* formulation of the problem.

The important factor to note here is that the Δp term represents the effective dynamic pressure. In order to make the limit state equation as

simple as possible and because Purcell, et al (1988) stated that the variation in longitudinal bending stress is very small relative to the stresses measured in the plate, all dynamic effects are combined into the Δp term. One should also note that the contribution of the transverse force N_y and the shearing force N_{xy} are considered to be small and are not included. This assumption is consistent with typical naval architecture design assumption. Principally, that is because solutions to equation (5-8) considering all terms would require a dynamic finite element analysis, something which is both time consuming and costly. Therefore, the measured stress due to the dynamic component of the pressure can be equated to the third term in equation (5-9) as follows:

$$\text{measured dynamic stress} = 36\, p^2 k^* \frac{b^4}{t_h^{\,4}} \qquad (5\text{-}10)$$

In order to use the theory of statistics of extreme as discussed in Section 4.3, the parent distribution for the measured stress needs to be defined. The stress due to the still-water pressure component should not be considered in the statistics of extreme analysis. The parent distribution of the stress is defined as the probability distribution of the maximum stress random variable in a conveniently selected time period.

According to available test results (Purcell, et al, 1988) and analysis (Ayyub and White, 1988) of the Island-Class patrol boat, the maximum stress random variable was defined in the center of the most highly stressed plate in the critical region as described in Chapter 3. This definition was in reference to a 30-second interval of measurement for all the operational combinations except combination 8 of Table 4-2. For combination 8, the interval is taken as 10 seconds. Based on this definition, the statistical characteristics of the parent distributions of stress for the eight combinations were determined. The results are summarized in Table 5-4. The mean values and coefficients of variation (COV) for cases 6 and 8 were based on 23 and 10 maximum values taken from 23 and 10 records of stress time-history, respectively. Each record represents the stress time-history for 30- and 10- second interval of measurement, respectively. For the other tests, one record per test was available to the researchers; therefore, the maximum value in each record was considered as the mean value of the maximum stress for the corresponding test and the coefficient of variation was assumed to be the same as the COV for case 6, i.e., 0.1.

Using the mean values of the maximum stress (Table 5-4), equation (5-10) was evaluated for the eight tests in order to obtain the mean value of the maximum pressure. The results are summarized in Table 5-5. It is reasonable to assume that the maximum dynamic pressure has the same coefficient of variation (COV) as the maximum measured stress. The mean value and COV of the extreme pressure were, then, determined using equations (4-11) to (4-14) for a boat usage period of 15 years at a rate of 3000 hours per year and according to the percent use presented in Table 4-2. The selection of the usage period of 15 years and the 3000 hours of operation per year are for the purpose of illustrating the results. The results are summarized in Table 5-5.

Table 5-4. Statistical Characteristics of the Maximum Stress (Ayyub and White, 1988)

Case Number	Interval	Mean Value	COV
1	30 sec.	2027 psi	0.1
2	30 sec.	2181 psi	0.1
3	30 sec	2303 psi	0.1
4	30 sec.	7136 psi	0.1
5	30 sec.	7818 psi	0.1
6	30 sec.	3556 psi	0.1
7	30 sec.	8821 psi	0.1
8	10 sec.	15462 psi	1.0

Table 5-5. Statistical Characteristics of Pressure

Case No.	Mean (P_{max}) (psi)	COV (P_{max})	No. of Intervals in Life, k	Mean ($P_{extreme}$) (psi)	COV ($P_{extreme}$)
1	1.75	0.0993	216000	2.55	0.0177
2	1.89	0.0993	91800	2.71	0.0186
3	1.99	0.0993	54000	2.83	0.0192
4	6.17	0.0993	253800	8.99	0.0175
5	6.76	0.0993	70200	9.66	0.0189
6	3.07	0.0993	37800	4.35	0.0196
7	7.63	0.0993	286200	11.13	0.0174
8	13.37	1.0121	162000	74.30	0.0477

It is evident from Table 5-5 that combination 8 for the Island-Class patrol boat is the most critical sea state/boat speed combination. For this case the mean value and COV of the maximum pressure are 13.37 psi and 1.00, respectively. Therefore, the mean value and the COV of the extreme pressure can be determined using the time periods of 0.2, 0.5, 1, 2, 5, 10, 15, 50 and 100 years. The results are shown in Table 5-6. The results presented in Table 5-6 are plotted in Figure 5-2. It is evident from this figure that the extreme pressure approaches a limiting value as the time increases, i.e., the extreme pressure shows an asymptotic behavior with increasing time.

In order to estimate the necessary maximum pressure in the time intervals, a transfer function that relates the maximum pressure to a calculated design pressure was developed based on the available test results and design calculations of the Island-Class patrol boat (Purcell, et al, 1988). The transfer function is a ratio of the maximum to design pressure for each of the eight cases (boat speed/sea state combinations). The calculated ratios can then be multiplied by the design pressure of any of the three patrol boats to obtain the corresponding maximum pressure for each case. For the Island-Class patrol boat, the design and maximum pressures for the eight combinations of the operational profile are summarized in Table 5-7.

Because the Heritage-Class patrol boat is being designed to perform the same mission as the Island-Class, the pressure ratios found for the Island-Class can satisfactorily be used for the Heritage-Class. The operational profile for the Cape-Class patrol boat, as shown in Table 4-4, has lower speeds than the Island-Class. The medium speed case for the Cape-Class, 12 kts, is the same condition as the low speed case for the Island-Class. Thus, the pressure ratios for the low speed combinations on the Island-Class were used for the medium speed combinations on the Cape-Class. This approach resulted in the necessary information in the critical combinations including combination 8 of the operational profile for the Cape-Class. The pressure ratios for the remaining five cases were estimated by interpolation of the Island-Class ratios.

Because of the limited number of data points, the determination of a function to describe the relationship between the design pressure and maximum pressure could not be developed. A number of curve and surface fitting techniques were tried and all met with limited success. Therefore, in this study, life expectancy of the structure can be determined at only the eight unique combinations of speed and sea state in head seas. These cases then have to be considered as capable of describing all of the head seas and speed operations of the boats in their life.

5.1.5 Strength Characteristics

The statistical characteristics of the strength of the material used in the Island-Class patrol boat, and the dimensions of the plate of interest in this study were determined by Ayyub and White (1987). Based of their results, information provided by plate steel manufacturers, and judgment, the statistical strength characteristics as shown in Table 5-8 were assumed.

Table 5-6. Statistical Characteristics of Pressure for Case 8

Usage Period (years)	No. of Intervals in Life, k	Mean ($P_{extreme}$) (psi)	COV ($P_{extreme}$)
0.2	2160	60.49	0.0732
0.5	5400	63.70	0.0657
1	10800	66.02	0.0610
2	21600	68.24	0.0569
5	54000	71.07	0.0523
10	108000	73.13	0.0493
15	162000	74.30	0.0477
50	540000	77.67	0.0435
100	1080000	79.54	0.0414

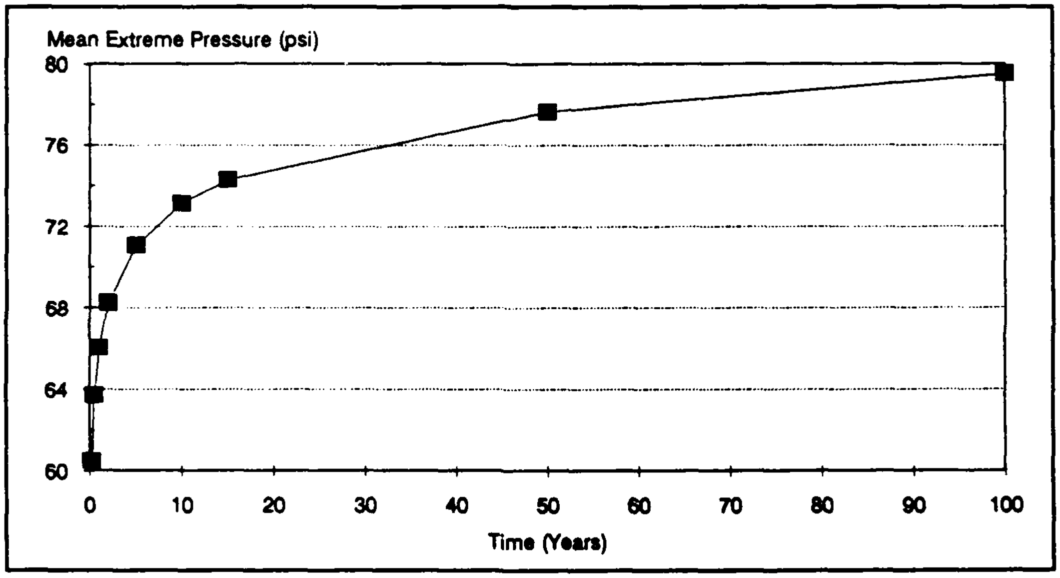

Figure 5-2. Asymptotic Behavior of Extreme Pressure

Table 5-7. Pressure Transfer Function

Case Number	Calculated Mean Maximum Pressure (psi)	Design Dynamic Pressure (psi)	Pressure Ratio (Maximum/Design)
1	1.75	13.50	0.1296
2	1.89	15.09	0.1253
3	1.99	15.75	0.1263
4	6.17	16.15	0.3821
5	6.76	20.38	0.3317
6	3.07	20.87	0.1471
7	7.63	17.21	0.4435
8	13.37	22.50	0.5943

5.1.6 Assessment of Probabilities of Failure for Plate Deformation

The probabilities of plastic deformation (P_{fp}) of a plate according to the limit state of equation (5-2) can be determined using Monte Carlo simulation with variance reduction techniques. Conditional Expectation with Antithetic Variates variance reduction techniques were used in the analysis. A computer program was developed for this purpose. The program is listed in Appendix C. The average simulated probabilities of failure (P_{fp}), and coefficients of variation of the estimate of the probability of failure COV(P_{fp}) for example selected time periods of the Island-Class patrol boat are shown in Table 5-9. In this example, two corrosion rates were considered, mean values of zero and 1 mpy and COV of 0.0001 and 0.1, respectively. The number of simulation cycles was selected to be 2000 cycles. The operational profile of the boat was considered to be non-random with 3000 hours of annual use and 1% use in case 8 of the operational profile. These results agree well with the study performed by Ayyub and White (1988). The cases presented in Table 5-9 and other cases were used to verify the developed computer program within the range of the parametric analysis that is presented in Chapter 9.

5.1.7 Assessment of Structural Life According to Plate Deformation

The end of the structural life of the forward bottom plating of a boat depends on many factors that include the rate of usage of the boat, loading condition and distribution, strength characteristics, the inspection and maintenance strategies, and the definition of end of structural life. Most of these factors were identified and defined in previous sections. The end of forward bottom plating structural life due to plate plastic deformation was defined in Chapter 3 as the plastic deformation of more than three times the thickness of the plate in at least a certain number of plates within the critical region. The number of plates and the critical regions were previously defined for the three boats. For example, the critical region for the Island-Class patrol boat was defined as the section of the boat between transverse bulkheads 13 and 17, and longitudinals 1L and 3L. There is a total of 28 plates in this section. These plates are assumed to experience the same loading and have approximately the same strength characteristics, therefore, have approximately the same probability of failure. The probability of failure, that is of interest in this study, is the unconditional one. Therefore, inspection and maintenance strategies are not considered. This means that the resulting probabilities of failure represent the probabilities of failure of the critical region as the exposure time to the loading increases, which is independent of inspection and maintenance.

Given the probability of failure of a plate (P_{fp}) as a function of time as discusses in Section 5.1.6, the probability of failure of the specified number of plates (np) within the critical region of Np plates ($P_{np/Np}$) can be determined using the probability mass function of the binomial distribution, where Np is the total number of plates in the critical region. The binomial distribution is based on a Bernoulli sequence of trials, i.e., failure of plates, which are assumed to be statistically independent. Actually, the events of plate failure are statistically correlated with relatively small correlation coefficients. The probability of failure of the plates is a function of the correlation

Table 5-8. Statistical Strength Characteristics

Strength Property	Island Class	Heritage Class	Cape Class
Steel Modulus of Elasticity:			
Mean Value (ksi)	29,774	29,774	29,774
COV	0.04	0.04	0.04
Steel Yield Strength:			
Mean Value (ksi)	47.8	64.0	38.0
COV	0.13	0.10	0.10
Plate Width:			
Mean Value (in)	11.75	12.0	18.0
COV	0.05	0.05	0.05
Plate Length:			
Mean Value (in)	23.5	42.0	72.0
COV	0.05	0.05	0.05
Thickness of Plate:			
Mean Value (in)	0.161	0.193	0.193
COV	0.01	0.01	0.01

Table 5-9. Deformation Probability of Failure of a Plate Example Cases for the Island-Class

Time Period (Years)	Wastage Rate = 0 mpy		Wastage Rate = 1 mpy	
	Probability of Failure	$COV(P_{fp})$	Probability of Failure	$COV(P_{fp})$
2	0.08636	0.038	0.10706	0.033
4	0.11465	0.032	0.16285	0.025
6	0.13355	0.029	0.21246	0.020
8	0.14803	0.027	0.25963	0.016
10	0.15986	0.026	0.30531	0.013
12	0.16991	0.025	0.34969	0.010
14	0.17868	0.024	0.39275	0.007
16	0.18646	0.023	0.43442	0.005
18	0.19347	0.022	0.47467	0.003
20	0.19984	0.022	0.51355	0.002
22	0.20570	0.021	0.55102	0.003
24	0.21112	0.021	0.58707	0.004
26	0.21617	0.020	0.62170	0.005
28	0.22088	0.020	0.65488	0.005
30	0.22532	0.019	0.68649	0.006

level. In this study, the failure of the plates is considered to be independent of the plates, i.e., the correlation level among plates is assumed to be zero. Therefore, $P_{np/Np}$ can be estimated in the form of the lower limit which correspond to a coefficient of correlation (ρ) of zero. Mathematically, the limits can be expressed as follows:

$$P_{np/Np} = \sum_{k=np}^{k=Np} \frac{(Np)!}{k!\ (Np-k)!} (P_{fp})^{k} (1-P_{fp})^{Np-k} \tag{5-11}$$

As an example, for the Island-Class patrol boat np=6 and Np=28, therefore, the resulting P_{fp} and $P_{f6/28}$ using the values in Table 5-9 and according to the above equation (5-11), are shown in Table 5-10. The probability of failure of the forward bottom plating of the boat due to plate deformation within its structural life (SL) is the same as $P_{fnp/Np}$. This relationship can be expressed as follows:

$$P_{fSL,y} = P_{fnp/Np} \tag{5-12}$$

The resulting probabilities in Table 5-10 are shown in Figure 5-3. These probabilities constitute a lower limit on structural life based on plate plastic deformation in the critical region. It should be noted that these results are highly dependant on the underlying assumptions. These assumptions include, for example, the 3000 hours of operation per year, the percent usage in each sea state/speed combination, loading conditions, definition of end of structural life, strength characteristics, etc.

5.2 FATIGUE

Fatigue and brittle fracture in boat structures is considered as one of the most critical failure modes. The structural Life of a boat according to fatigue and brittle fracture failure mode can be determined in several steps that are discussed in the following sections.

5.2.1 Limit State Equation

The fundamental relationship for the analysis undertaken in this part of the study can be expressed in the form of a simple limit state equation as

$$g(X) = \text{Resistance} - \text{Load} \tag{5-13}$$

For the purpose of fatigue analysis, equation (5-13) is usually handled in one of two ways; either using stress range versus number of cycles to failure (S-N) fatigue test data, or from the principles of fracture mechanics. In this study, an S-N relationship approach was undertaken because of the familiarity of the Coast Guard Office of Engineering personnel with the approach, the popularity of the approach, and the method is consistent with current inspection and maintenance practices of Coast Guard. Munse et al (1982) provided an in depth discussion concerning this approach as well as much of the needed S-N data to accomplish the tasks.

Table 5-10. Plate Deformation Probability of Failure
Single Plate and 6 Out of 28 Plates

Time Period (Years)	Wastage Rate = 0 mpy		Wastage Rate = 1 mpy	
	P_{fp} Probability	$P_{f6/28}$ Probability	P_{fp} Probability	$P_{f6/28}$ Probability
2	0.08636	0.0297	0.10706	0.0722
4	0.11465	0.0938	0.16285	0.2998
6	0.13355	0.1619	0.21246	0.5647
8	0.14803	0.2260	0.25963	0.7724
10	0.15986	0.2844	0.30531	0.8982
12	0.16991	0.3369	0.34969	0.9604
14	0.17868	0.3840	0.39275	0.9864
16	0.18646	0.4263	0.43442	0.9959
18	0.19347	0.4643	0.47467	0.9989
20	0.19984	0.4986	0.51355	0.9997
22	0.20570	0.5297	0.55102	0.9999
24	0.21112	0.5578	0.58707	1.0000
26	0.21617	0.5835	0.62170	1.0000
28	0.22088	0.6069	0.65488	1.0000
30	0.22532	0.6283	0.68649	1.0000

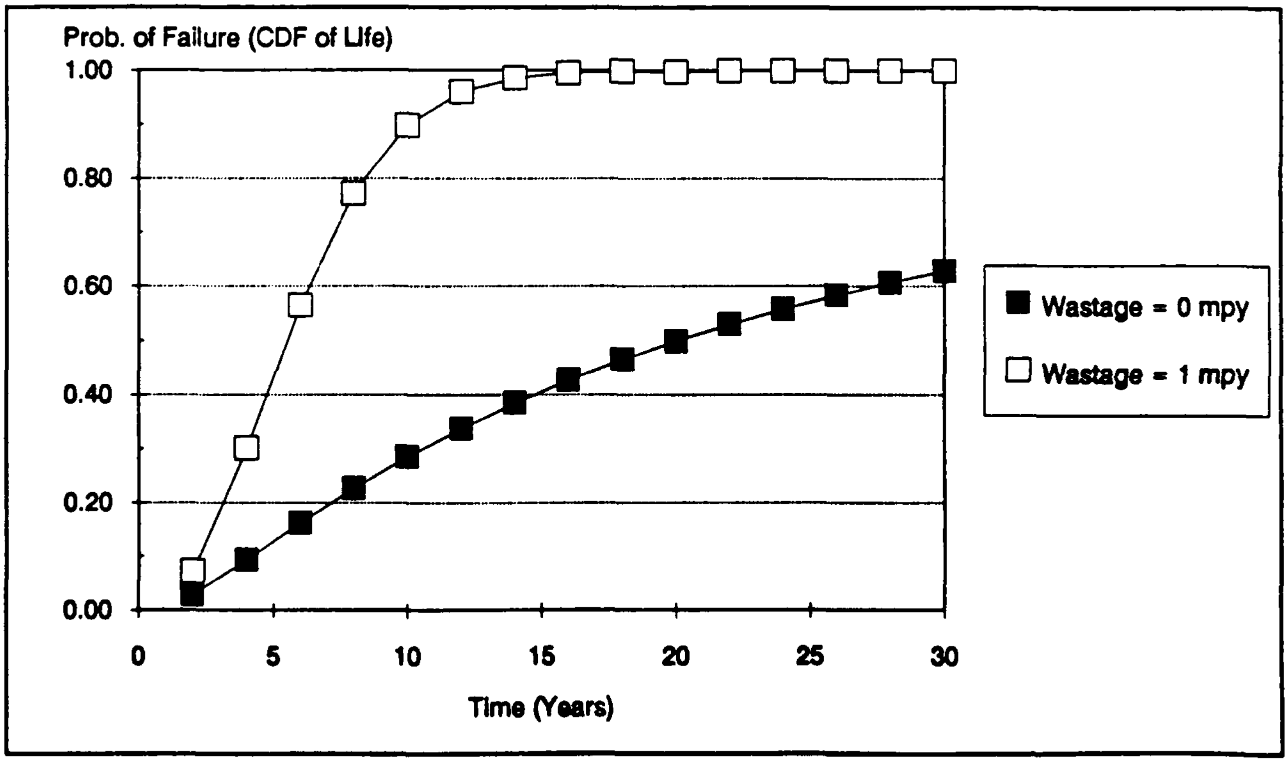

Figure 5-3. Structural Life Based on Plate Deformation for the Example Case

For the case of fatigue analysis of structural details, the resistance is expressed in terms of the strength characteristics of the various local fatigue details that make up the particular structural connection of interest. The S-N curves provide information concerning stress range to life relationship usually expressed in terms of a constant amplitude stress range. A least squares regression line through the mean values of life at each stress range tested provides a curve which can be expressed in a log-log linear form as (White and Ayyub, 1987)

$$\log N = \log C - m \log S_R \qquad (5\text{-}14)$$

where S_R is the constant amplitude stress range at N cycles to failure; the regression coefficients are the negative inverse of the S-N curve slope, m, and the intercept, $\log C$. This equation is also commonly expressed in terms of stress range as

$$S_R = (C/N)^{1/m} \qquad (5\text{-}15)$$

The loading term in equation (5-13) is represented by an *equivalent constant amplitude stress range* for the lifetime load histogram for the fatigue detail of interest. Appendix A.2 more thoroughly covers the development of the equivalent constant amplitude stress range, Section 5.2.2 covers the development of the lifetime load histogram.

Because the loading in equation (5-13) is represented as a single value, the solution for the probability of having a fatigue failure in a given lifetime reduces to

$$P_{ff} = P(N_d \leq N) \qquad (5\text{-}16)$$

Here N is a random variable representing the number of loading cycles which the detail of interest can survive at the equivalent constant amplitude loading from the lifetime histogram. The random variable N_d represents the number of loading cycles expected in the life of the vessel based on the lifetime load histogram. It can be based a mean loading cycles of 1402 per hour, COV of 0.3 and normal distribution type (Ayyub and White, 1988). The solution to equation (5-16) can be achieved using Monte Carlo simulation.

5.2.2 Load Effect Histograms

In order to evaluate equation (5-13), an expression for the loading expected in the vessel's lifetime needs to be developed. The ideal form for the loading information is a histogram (or a probability density function, PDF) relating stress ranges to frequency of occurrence. Such a histogram or PDF could then easily be related to an equivalent constant amplitude stress range, as shown by Munse (1982) and expressed in Appendix A.2.

In this study, the stress time-history results based on testing an Island-Class boat in the eight combinations of sea state and boat speed of the operational profile (Purcell, et al, 1988), and the analysis of these results (Ayyub and White, 1988) are used. The stress records of the eight tests that correspond to the eight cases as shown in Table 4-1 were studied to determine the stress range cycles encountered during the duration of the

tests. A "Rainflow Counting Method" (Fuchs and Stephens, 1980) was used to build a frequency histogram of stress ranges for each test. The individual histograms were then weighted by their respective percent usage factors from Table 4-1 and combined to form a stress range frequency histogram for head seas. This histogram represents the distribution of *Von Mises* (Beer and Johnston, 1981) stresses experienced at the center of one panel of the bottom plating of the test vessel. This histogram is shown in Figure 5-4.

The resulting histogram needs to be adjusted according to boat class and the local fatigue detail for the boat under consideration. A means of relating the stress ranges of the histogram to the stress ranges at points of interest in a boat needs to be developed. This can be accomplished by using stress transfer functions.

5.2.3 Stress Transfer Functions

There are two types of needed transfer functions, boat-stress transfer functions and fatigue detail-stress transfer functions. Both types of transfer function should be used to calculate the total transfer function.

Boat-Stress Transfer Functions. This stress ratio is needed to relate the measured *Von Mises* stress at the center of a highly stressed plate within the critical region of the Island-Class patrol boat to the calculated *Von Mises* stress at the center of a highly stressed plate within the critical regions of the Heritage and Cape-Class patrol boats. The stress calculations are based on the analysis of a plate with fixed boundary conditions using a method suggested by Mansour (1967), and assuming in-plane loads due to hull bending to be negligible. The results for determining the boat-stress transfer functions T_b are summarized in Table 5-11. The boat-stress transfer ratios in the table are based on the *Von Mises* stresses at the center of the plates, and are determined using the following equation:

$$\text{Boat-Transfer Function, } T_b = \frac{\textit{Von Mises}\text{ Stress for a Boat Class}}{\textit{Von Mises}\text{ Stress for Island-Class}} \qquad (5\text{-}17)$$

Detail-Stress Transfer Functions. These transfer functions relate the *Von Mises* stresses at the center of a plate within the critical region of a boat to the applied stress for the different boat-specific fatigue details. The applied stresses for the fatigue details are defined as the maximum principal stresses that are similar (or equivalent) to the ones used by Munse, et al (SSC-318, 1982) in the development of the S-N curves for the different fatigue details. In order to determine these transfer functions, a basic analysis of the structural connections based on the concepts of structural analysis and mechanics of materials were performed to determine the applied stress for each fatigue detail within the critical regions of the three boat classes. The results for the Island-Class patrol boat based on this type of analysis agree fairly well with the results of finite element analyses of the four critical structural connections that were previously identified. The *Von Mises* stress at the middle of the plate for each boat class was determined and is shown in Table 5-11. The applied stresses for the fatigue details were determined and are shown in Table 5-12. Details of the calculations for the fatigue detail stress levels are

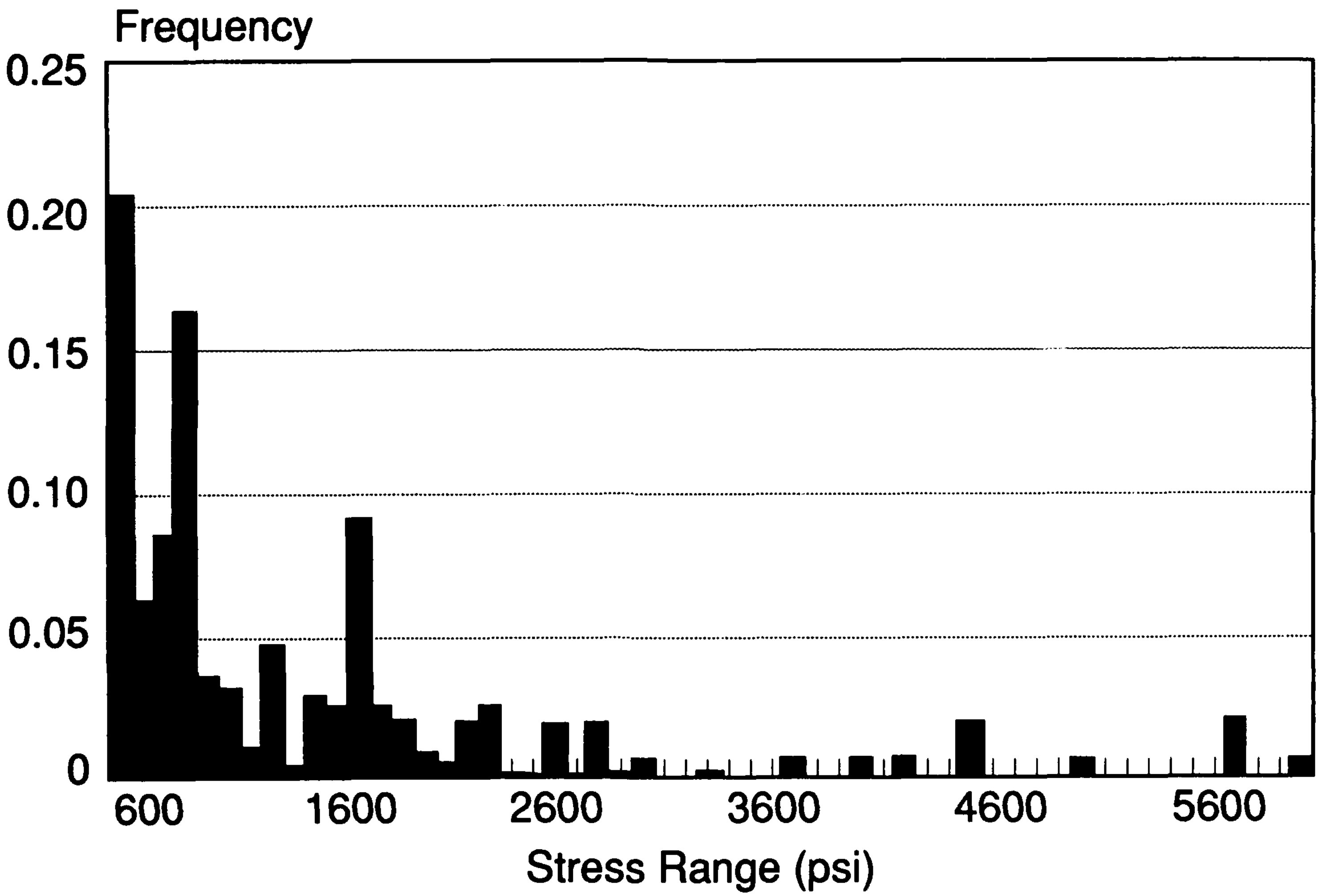

Figure 5-4. Total Stress-Range Histogram for Head Seas for the Island-Class Patrol Boat

Table 5-11. Boat-Stress Transfer Functions

Parameter	Island	Heritage	Cape
	Patrol Boat Class		
Plate Size:			
Length	23.5 in	42.0 in	72.0 in
Width	11.75 in	12.0 in	18.0 in
Thickness	0.160 in	0.1930 in	0.1875 in
Aspect Ratio	2	3.5	4.0
Pressure Load	1 psi	1 psi	1 psi
Mansour's Method:			
Gamma	0.04	0.0417	0.0417
Beta	0.004	0	0
Principal Stress:			
Sigma X	511.32 psi	290.17 psi	652.89 psi
Sigma Y	1316.66 psi	967.24 psi	2176.29 psi
Von Mises Stress	1149.69 psi	859.70 psi	1934.33 psi
Transfer Function	1.0	0.7477	1.6825

Table 5-12. Detail-Stress Transfer Funtions

Fatigue Details	Stress Transfer Values					
	Island-Class		Heritage-Class		Cape-Class	
	Detail	Total	Detail	Total	Detail	Total
4	0.05	0.05				
10A	0.03	0.03				
11					0.19	0.3197
20			0.37	0.2767		
21			0.37	0.2767		
25	0.10	0.10				
26			0.79	0.5907		
28F			0.37	0.2767	0.01	0.0168
36(Long'l)	0.21	0.21	0.47	0.3514	0.36	0.6057
36(Trans)			0.51	0.3814	0.14	0.2355
39			0.37	0.2767	0.36	0.6057
49					0.13	0.2187
51			1.17	0.8749		

provided in Appendix B. The detail-stress transfer functions T_d were then determined as follows:

$$\text{Detail-Transfer Function, } T_d = \frac{\text{Applied Stress for detail}}{\textit{Von Mises} \text{ Stress at Mid-Plate}} \tag{5-18}$$

The total transfer function is determined as the product of the boat and detail transfer functions, i.e, the product of equations 5-17 and 5-18.

5.2.4 Fatigue Strength Characteristics

The identified 13 local fatigue details for all boat classes are coded and classified according to the fatigue detail classification by Munse, et al in SSC-318 (1982). The stress range vs. number of cycles to failure (S-N) curves and their statistical characteristics are taken from SSC-318. The fatigue strength characteristics of details 25, 11, 36, 4, 10A, 20, 21 and 26 are summarized in Table 5-13. The fatigue strength characteristics of details 39, 28F, 51, and 49 are not available in SSC-318 (1982). However, there are similar details which are believed to have similar fatigue strength characteristics. These details are 38, 28, 51(V) and 51(or 52) which are similar to details 39, 28F, 51, and 49, respectively. The fatigue strength characteristics are also shown in Table 5-13. The *Weibull* probability distribution is used to model fatigue strength. The parameters of the distribution are shown in the same table.

The standard deviation of the fatigue strength (life) can easily be found; however, the scatter of the data about the mean fatigue line is not the only uncertainty involved in the S-N analysis. A measure of the total uncertainty (coefficient of variation) in fatigue life, v_R, is usually developed to include the uncertainty in fatigue data, errors in the fatigue model, and any uncertainty in the individual stresses and stress effects. The total COV in terms of fatigue life is given by (Ang and Munse 1975):

$$v_R^2 = v_N^2 + v_F^2 + v_C^2 + (m v_S)^2 \tag{5-19}$$

where

- v_R - total COV of resistance in terms of cycles to failure
- v_N - variation in fatigue test data about mean S-N line
- v_F - variation due to errors in fatigue model and use of Miner's rule
- v_C - variation due to uncertainty in mean intercept of the regression line; includes effects of fabrication, workmanship, and uncertainty in slope
- v_S - variation due to uncertainty in equivalent stress range; includes effects of error in stress analysis
- m - slope coefficient of mean S-N regression line

Values of m and v_N can be obtained from sets of S-N curves for the type of detail being investigated; a number of which are tabulated by Munse in SSC-318. Reasonable values for the remaining uncertainties are available in the literature (Thayamballi, 1984; Ang, 1975; Munse, 1982). Typically, v_S is taken to be 0.1, v_C is assumed to be 0.4, and v_F is taken as 0.15.

5.2.5 Assessment of Probabilities of Failure

Using the stress-range histograms due to the dynamic pressure, an equivalent constant amplitude stress range S_c that causes the same damage on a fatigue detail as the measured variable amplitude stress-range histogram. The conversion was performed using the slope coefficient of the S-N mean line *m* of the local fatigue detail. Mathematically, the conversion is given by

$$S_c = [E(S^m)]^{1/m} \tag{5-20}$$

where $E(S^m)$ is the expected value of the variable amplitude stress range raised to the m^{th} power. The resulting S_c is multiplied by the stress ratios (or transfer functions) that pertains to each boat and local fatigue detail. Then, the resulting constant amplitude stress range is used to determine the mean value of fatigue life (in cycles to failure) from the S-N curve for each local fatigue detail. The fatigue strength of a fatigue detail is assumed to follow a *Weibull* distribution. The parameters of the *Weibull* distribution are shown in Table 5-13. For any time period, the number of stress-range cycles in this period can be determined. The number of cycles in the period is determined based on the annual number of hours of operation and a weighted average of measured stress cycles per hour which are random variable as previously described.

The probability of failure of a local fatigue detail to reach the total number of cycles in a time period N_d can be determined using Monte Carlo simulation with VRT. For example, for the Island-Class patrol boat with an example non-random annual number of operational hours of 3000 hours and loading cycles of 1402 per hour, the resulting probabilities are shown in Figures 5-5 to 5-8. The total number of critical local fatigue details depends on the identified critical region of the boat. The region which was identified for the Island-Class boat is between 1L and 3L, and transverse frames 13 and 17. The number of local details were counted and reported previously in Table 3-2. The forward bottom plating end of structural life for this mode of failure was defined as the failure of one or more local fatigue details at any time. The probability of failure of at least one detail out of the number of details at the end of any time period can be taken as the maximum failure probability of any detail, based on the assumption of highly correlated fatigue details. The resulting probabilities are the same as in Figures 5-5 to 5-8 for the five local fatigue details within the critical region of the Island-Class patrol boat.

5.2.6 Assessment of Structural Life According to Fatigue Failure

The structural life of the forward bottom plating of a boat is dependent on the inspection strategy. According to current inspection and maintenance practices of the U.S. Coast Guard, fatigue inspection entails for visual inspection and search for any fatigue cracks. In order to find any fatigue cracks according to such a method, the cracks need to be at a relatively advanced stage of propagation. Therefore, the S-N approach as described in the previous sections provides the necessary prediction tools of fatigue structural life. Inspection and maintenance strategies need not to be considered. The implied inspection and maintenance assumption in

Table 5-13. Fatigue Strength Characteristics of Local Fatigue Details

Detail No.	S-N Characteristics				Weibull Parameters	
	m	Log C	v_N	v_R	w	k
4	5.663	14.22	0.61	0.936	1.29E10	1.069
10A	5.468	14.14	0.79	1.051	4.33E14	0.952
11	5.765	13.77	0.68	0.989	3.71E12	1.011
20	4.619	11.57	0.66	0.912	6.45E08	1.098
21	14.245	26.72	0.83	1.703	2.27E12	0.616
25	7.090	15.79	0.78	1.137	2.53E[illegible]	0.882
26	3.348	10.13	0.61	0.817	4.36E0[illegible]	1.230
28F	7.746	17.41	0.81	1.199	9.63E10	0.838
36	6.966	15.15	0.63	1.032	6.82E08	0.969
39 (38)	3.462	10.17	0.36	0.657	3.94E08	1.554
49 (51 & 52)	3.930	11.09	0.13	0.595	1.18E09	1.734
51(V)	3.818	10.93	0.07	0.577	1.06E09	1.792

fatigue is that no inspection and maintenance is performed before the development of fatigue failure, i.e., crack.

The structural life, also, depends on the correlation level between the fatigue details, which is unknown. The determination of structural life can be performed for the two limiting cases that correspond to correlation levels of statistically independent, i.e., coefficient of correlation equals zero, and fully correlated, i.e., coefficient of correlation equals one. Since fatigue damage is cumulative in nature, the same welding process is used for all fatigue details and the same source of loading for all fatigue details, the coefficient of correlation between local fatigue details of the same type can be assumed to be large, i.e., close to the fully correlated limiting value. Therefore, for any time period, the probabilities of fatigue failure of the forward bottom plating of a boat are the corresponding maximum values of the probabilities of failure of all local fatigue details within the critical region of the boat. For example, for the Island-Class patrol boat, the probabilities of failure of four fatigue details 25, 36, 4 and 10A are shown in Figures 5-5 to 5-8, respectively. The fatigue structural life expectancy of the critical region of a boat is the curve that corresponds to the largest probabilities of failure among the fatigue details. For this example case, fatigue detail 36 is the maximum curve that represents structural life expectancy $P_{fSL,f}$ in fatigue. This curve is shown in Figure 5-9.

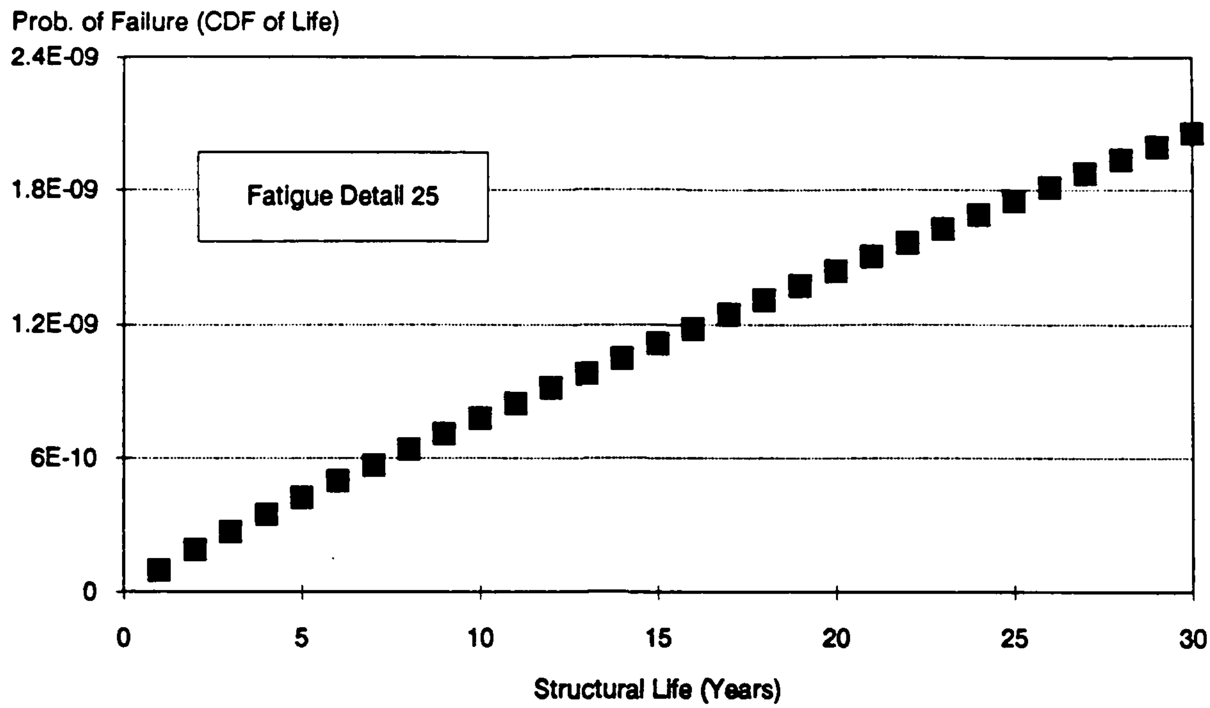

Figure 5-5. Probabilities of Failure for Local Detail No. 25

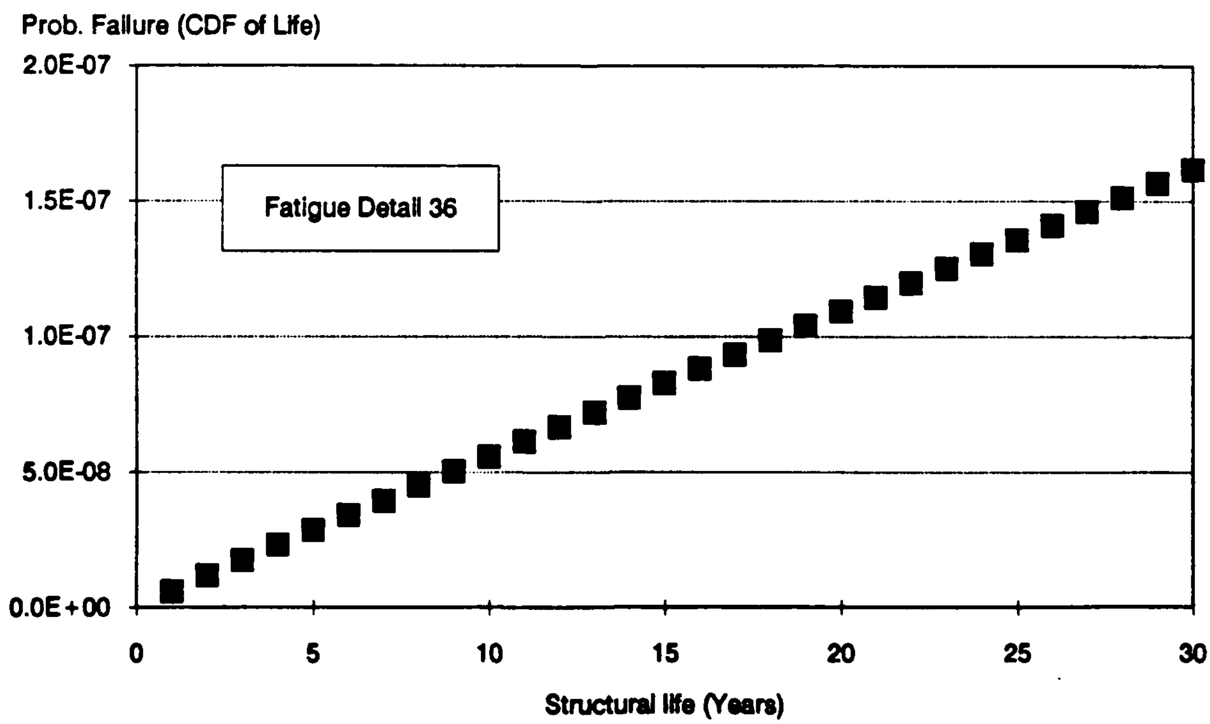

Figure 5-6. Probabilities of Failure for Local Detail No. 36

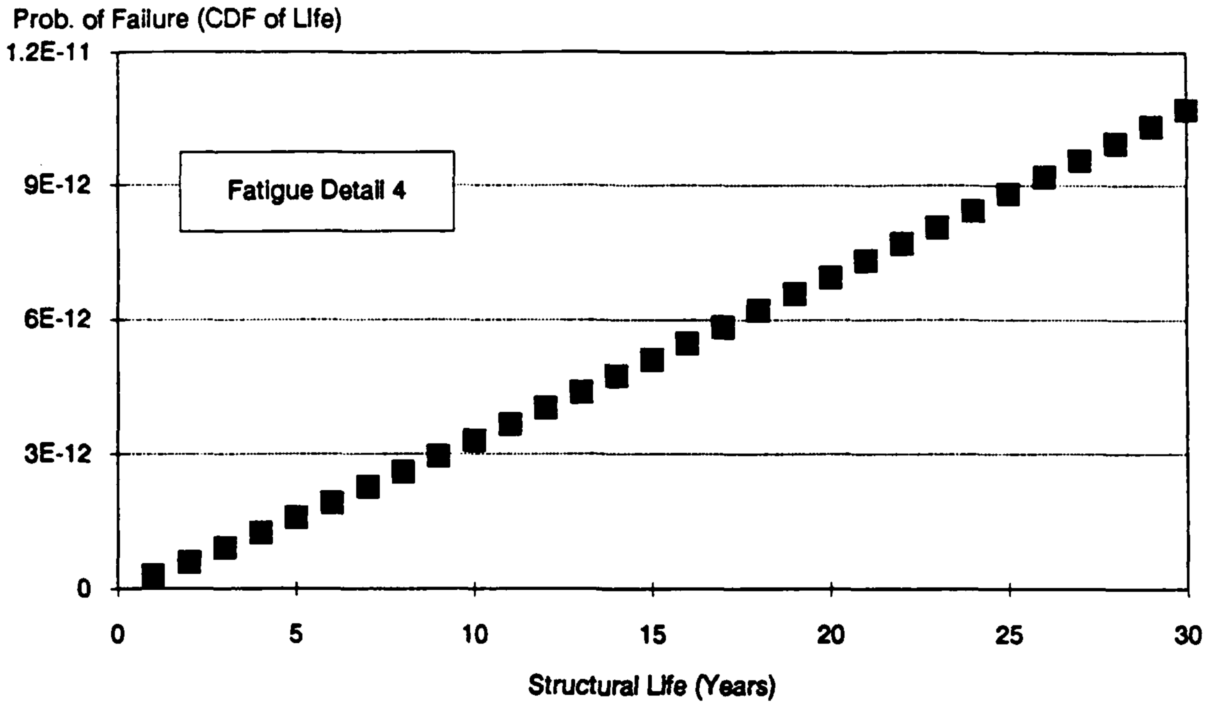

Figure 5-7. Probabilities of Failure for Local Detail No. 4

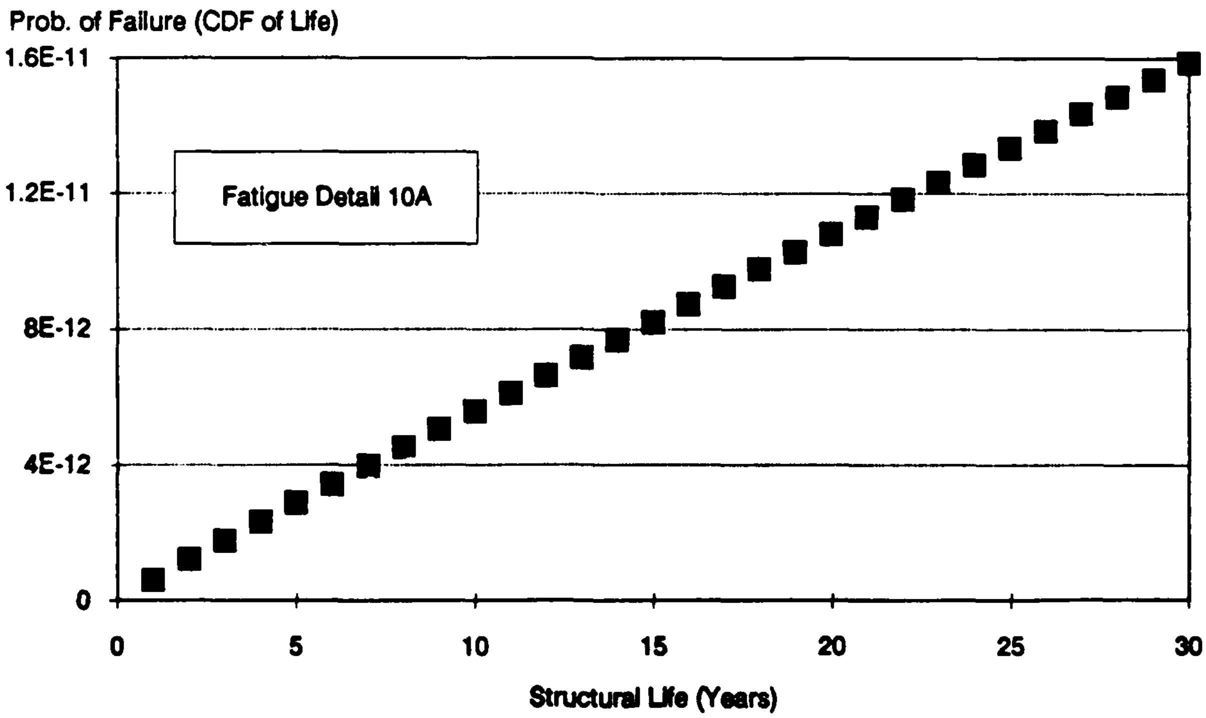

Figure 5-8. Probabilities of Failure for Local Detail No. 10A

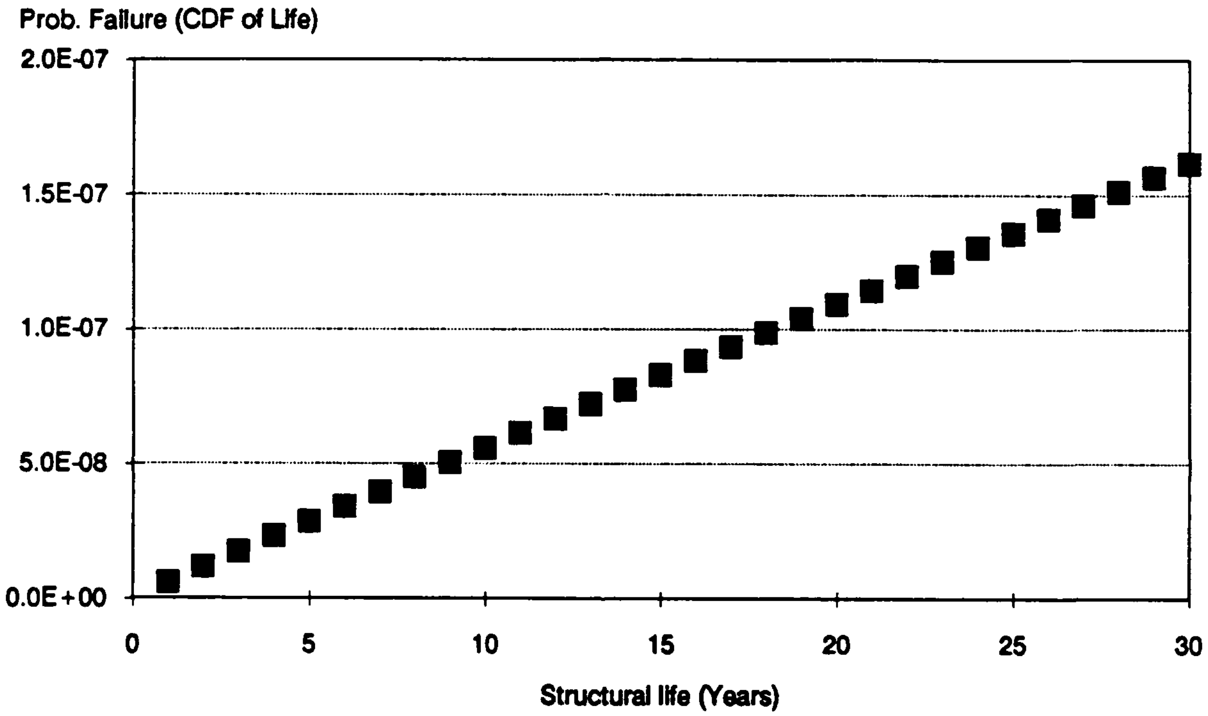

Figure 5-9. Structural Life Based on Fatigue Failure for the Example Case

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6. STRUCTURAL LIFE ASSESSMENT OF THE SYSTEM

The structural system of the boat can be modeled as bi-element system in series. The two elements correspond to the identified two most critical structural failure modes, i.e., plate plastic deformation, and fatigue and brittle fracture. These two failure modes are considered to be statistically correlated. The level of correlation is dependent on many factors which include; loadings, material properties, construction parameters, etc. The evaluation of the correlation level can be a difficult task. Therefore, bounds on the probability of failure and, consequently, the structural life expectancy are developed. The upper bound of the probability of failure of the system corresponds to high correlation level between the failure modes,i.e., a correlation level that is equal to one. The lower limit on the probability of failure of the system corresponds to zero correlation level. Mathematically, the probability of failure of the system is bounded as follows:

$$\text{Maximum}\ (P_{fSL,y}, P_{fSL,f}) \leq P_{fSL} \leq 1 - (1 - P_{fSL,y})(1 - P_{fSL,f}) \qquad (6\text{-}1)$$

For the example case of the Island-Class patrol boat (Figures 5-3 and 5-9), the probabilities of system failure of the forward bottom plating of the boat as a function of structural life are shown in Figure 6-1. These probabilities of failure can be considered the same as the cumulative distribution function of structural life.

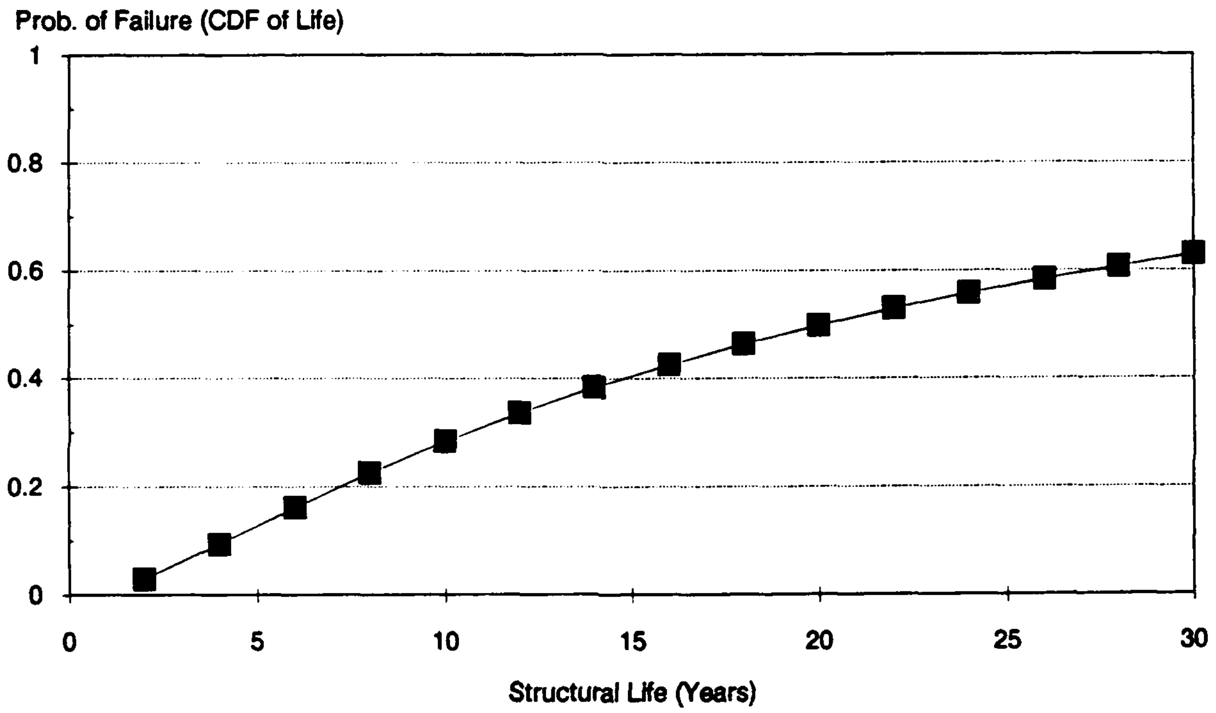

Figure 6-1. Limits on Structural Life for the Example Case - Island-Class

7. CALIBRATION OF THE MODEL

7.1 SELECTION OF CRITERIA

The suggested analytical model for structural life expectancy of patrol boats is tested and calibrated using available service record information for the Cape-Class (95 ft. WPB) patrol boat. The primary functions of these patrol boats are search and rescue and law enforcement missions. Some of these boats reached the end of their structural design life of 30 years, e.g., the CGC Cape Fairweather (WPB 95314) which was decommissioned in early March 1985. The Cape Fairweather was visually inspected and photographed as reported by Rosenblatt, 1985. The vessel had experienced local deformations in the shell, decks and bulkheads in many areas due to local impacts. Plastic permanent deformation or "dishing" of the shell, deck and bulkhead plating between stiffeners was reported to have occurred throughout the vessel. Local buckling of the plating of the main deck, just forward of the deckhouse, on both the port and starboard deck edges was observed. The forward bottom plating between bulkheads 27 and 39 was heavily dished. The maximum depth of dishing was two inches which corresponds to w_p/t_h ratio of about 10. The forward bottom plating between bulkheads 9 and 39 had a number of cracks at the plating and the seams.

Similarly, the Corwin (WPB 95326), Knox (WPB 95321) and Upright (WPB 95303) Cape-Class patrol boats were inspected for damage by Rosenblatt (1985). The most structurally damaged regions in these boats were within the vicinity of the critical region of the Cape-Class patrol boat as was previously defined in Chapter 3. The results of the survey are summarized in Table 7-1. The damage results were reported in the form of damage points that range from zero, which corresponds to no damage, to four, which corresponds to failure. The ages of these boats at the end of 1985 were reported as shown in the table. Since the Fairweather (WPB 95314) was decommissioned in early March 1985, it can be considered to have reached its end of structural life. Therefore, a probability of failure of one can be assigned to the WPB 95314 at that age. Based on this probability and the boat's total damage points of 21, the probabilities of failure of the three boats can be determined at the ages of 30 and 27 years in the form of normalized damage. The resulting probabilities of failure are shown in Table 7-1 as normalized damage. The total damage of each boat is normalized with respect to the maximum total damage of WPB 95314, i.e., total points of 21.

Based on the results of this study (Table 7-1), it can be concluded that the proposed analytical model should result in probabilities of failure of the critical region (forward bottom plating) for the Cape-Class patrol boat in the plastic plate deformation and fatigue failure modes of about 0.6 at 27 years and 0.81 at 30 years. The evaluation should include some allowance for plate wastage, even though the plating was galvanized. In this study, however, plate wastage was not included in the model for the Cape-Class patrol boat.

7.2 ADJUSTMENT AND VERIFICATION OF THE MODEL

The calibration of the model, and the comparative and parametric analysis require the definition of a set of reference input cases for the three boats. These reference boat cases are defined in Table 7-2. They are used as bases for comparison among boats, and for parametric variation in the parametric analysis. In Table 7-2, all the needed input parameters are shown except the operational parameters in speed/sea state combinations 1 to 7, COV and distribution types for the strength and loading basic random variables. These parameters and statistical characteristics were not varied in the calibration, comparative and parametric analyses, and are kept at the same levels as set in previous sections of this report.

Based on inspection of the input parameters for the Cape-Class patrol boat, the plastic deformation to thickness ratio w_p/t_h was selected as a control variable for the purpose of calibrating the suggested analytical model. This deformation parameter was varied from 3 to 6 in an increment of 0.25. The analytical model was, then, exercised using the operational profile, loading and strength characteristics of the Cape-Class patrol boat, and the results were compared to the criteria presented in Section 7.1. The ratio of 4.75 resulted in the best agreement for the Cape Class between the estimated probability of failure at 30 years and the criteria presented in Section 7.1. The results of this analytical case are shown in Figure 7-1.

For the Island and Heritage classes, the panels within their respective critical regions are smaller than the panels within the critical region of the Cape Class. Since visual inspection and characterization of plate deformation damage is dependent on panel size, the plate deformation ratio should be corrected to account for the panel size. Therefore, the ratio for the Island and Heritage classes can be determined as 66% (based on the panel width ratios, 12 in/18 in) of the 4.75 ratio, and is taken to be approximately 3 in this study.

Table 7-1. Damage Assessment of Cape-Class Patrol Boats

Parameter	WPB 95314	WPB 95326	WPB 95312	WPB 95303	Total Damage
	Damage Points[1]				
1. Source of Damage					
Slamming	3	3	2	1	9
Striking	3	1	2	2	8
Wave Slap	4	2	0	0	6
Cavitation	1	1	3	3	8
Loading/Vibration	2	1	2	3	8
Fatigue/Corrosion	2	2	3	3	10
Deterioration	3	1	2	4	10
Drydocking	3	1	3	1	8
Total Points	21	12	17	17	
2. 1985 Boat Age	>30	27	30	30	
3. Normalized Damage Prob. of Failure	1.0	0.5714	0.8095	0.8095	

[1] Damage Points: 0-no damage, 1-very slight damage, 2-light damage, 3-severe damage, and 4-failure

Table 7.2 Reference Boat Cases

Parameter	Island Class	Heritage Class	Cape Class
1. **Boat Information:**			
Displacement	165.1	161.8	105.0
L_{WL}	104.	110.	90.
Draft	6.48	4.50	6.00
Chine Length	104.00	110.00	90.00
Chine Beam	19.5	20.8	18.5
Deadrise Angle	12.0	19.0	15.0
Annual Use	2167	2167	1410
2. **Plate Deformation Failure Mode:**			
Failure Criteria	6/28	4/20	2/8
Speed/Wave Height for *Case 8*	24/10	24/10	12/10
Percent Use in Case 8	1	1	1.4
Mean Max. Dynamic Pressure	13.37	10.77	5.24
Mean Static Pressure	2.667	2.00	2.00
Plate Width	11.75	12.00	18.00
Plate Length	23.5	42.0	72.0
Plate Thickness	0.161	0.193	0.193
Modulus of Elasticity	29774	29774	29774
Yield Strength	47.8	64.0	38.0
Plate Wastage	1.	1.	0.
Percent Headseas Use	19.7	19.7	20.0
Deformation Ratio	3.0	3.0	4.75
3. **Fatigue Failure Mode:**			
Loading Cycles/hour	1402	1402	1402
Local Detail Type	36, 25 10A, 4	36, 20 21, 39 26, 51 28F	36, 39 11, 49 28F
4. **Simulation Cycles:**			
Plate Deformation	2000	2000	2000
Fatigue	500	500	500

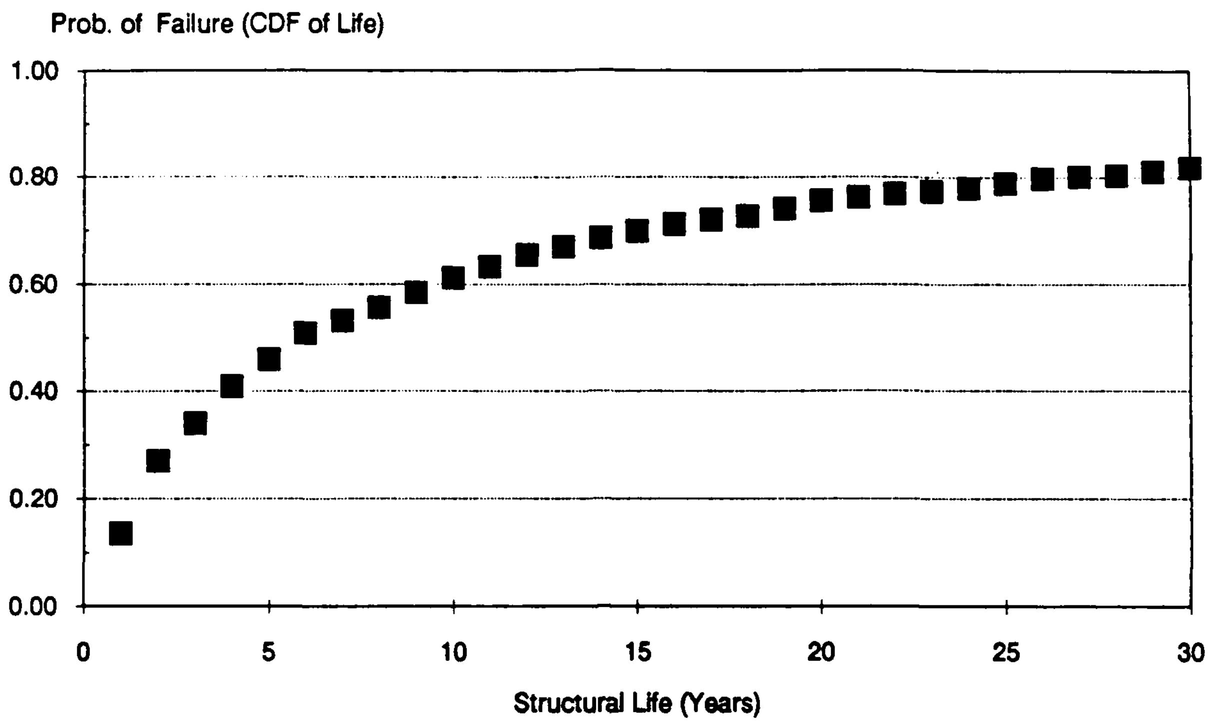

Figure 7-1a. Structural Life Expectancy Based on Plate Deformation for the Cape-Class

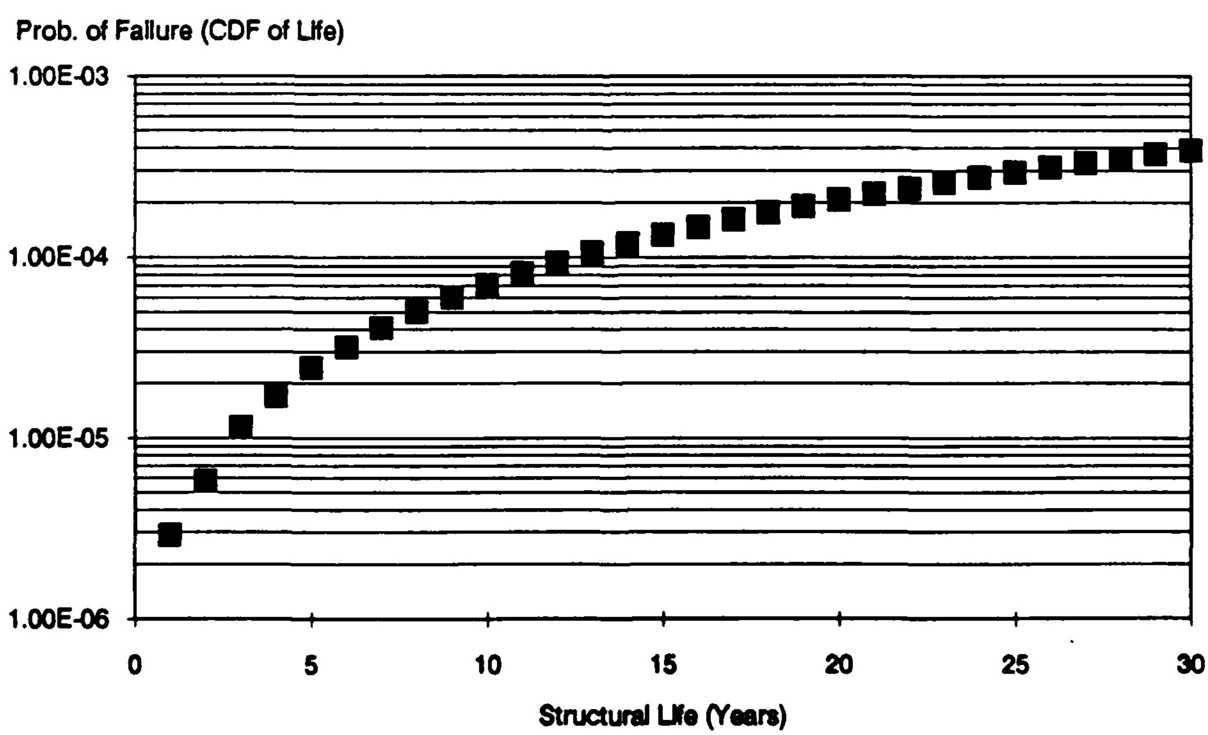

Figure 7-1b. Structural Life Expectancy Based on Plate Fatigue for the Cape-Class

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8. COMPARATIVE ANALYSIS

8.1 DEFINITION OF CRITERIA

The reliability-based evaluation of the structural life expectancy of the forward bottom plating was performed for the Island and Heritage-Class patrol boats using the strength, operational profile and load effect parameters for the corresponding boat. The two boats were analyzed under the same conditions of loading and operational parameters. The strength characteristics and definition of the critical region are, of course, different for the two boats as were discussed in previous sections of this report. The main input parameters are defined as the reference boat cases in Table 7-2.

8.2 RESULTS AND DISCUSSION

The results of the comparative evaluation are presented in Figures 8-1 to 8-4. The results are separately presented for the plate deformation and fatigue failure modes for each boat. Then, the results of the failure modes for each boat are combined to obtain limits on the probability of failure of the structural system, as shown in Figures 8-5 and 8-6 for the Island and Heritage-Class patrol boats, respectively.

Based on this analysis of the forward bottom plating, the life expectancy of the Island-Class patrol boat in the fatigue failure mode was determined to be slightly better than the Heritage-Class patrol boat. However, the probabilities of failure in fatigue for both boats were within the acceptable limits. Generally, one or more structural details have major effects on this result. In this case, the most critical fatigue detail in the Heritage-Class patrol boat is #26 used at the intersections of the longitudinals with bulkheads. Figure 8-7 shows the details of this intersection for both boats. In the plate deformation failure mode, the Heritage-Class patrol boat was determined to be significantly better than the Island-Class patrol boat. This is due to the relatively thin plating used in the construction of the Island-Class patrol boats. In the structural system analysis, the failure mode with larger probabilities of failure significantly drives the results. Therefore, the system's probabilities for the Island-Class patrol boat are driven by the plate deformation failure mode, whereas the system's probabilities for the Heritage-Class patrol boat are driven by the fatigue failure mode.

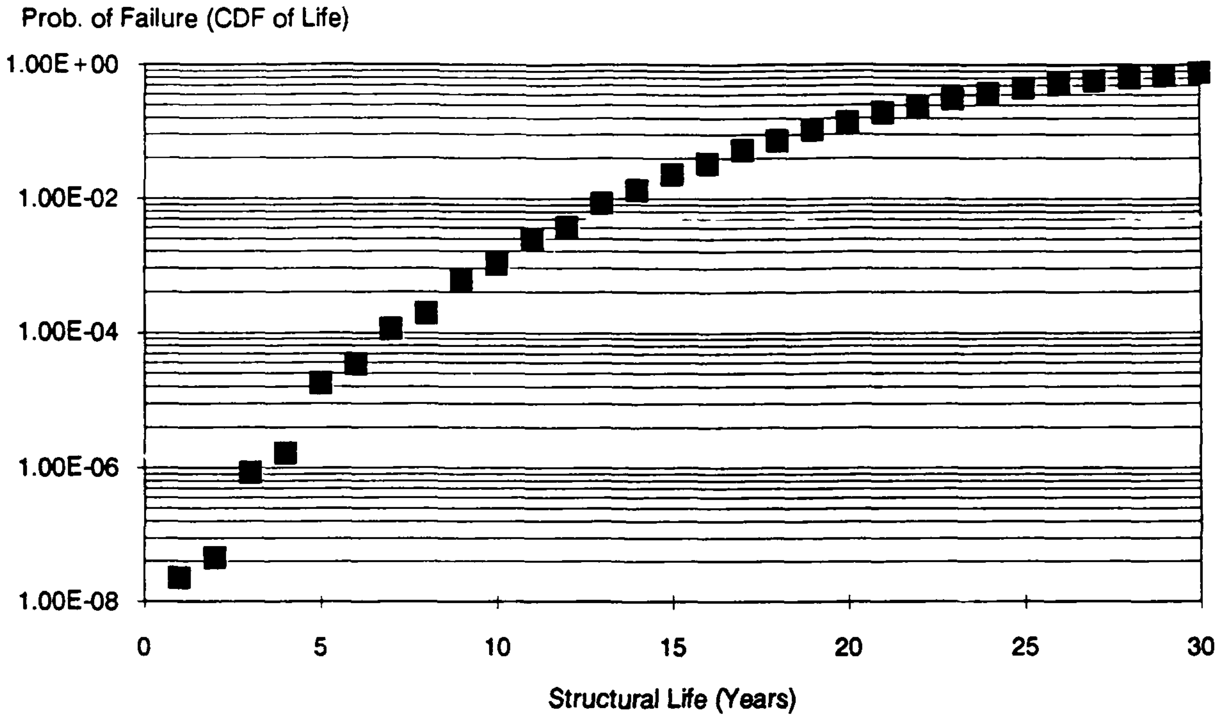

Figure 8-1. Structural Life Expectancy Based on Plate Deformation for the Island-Class

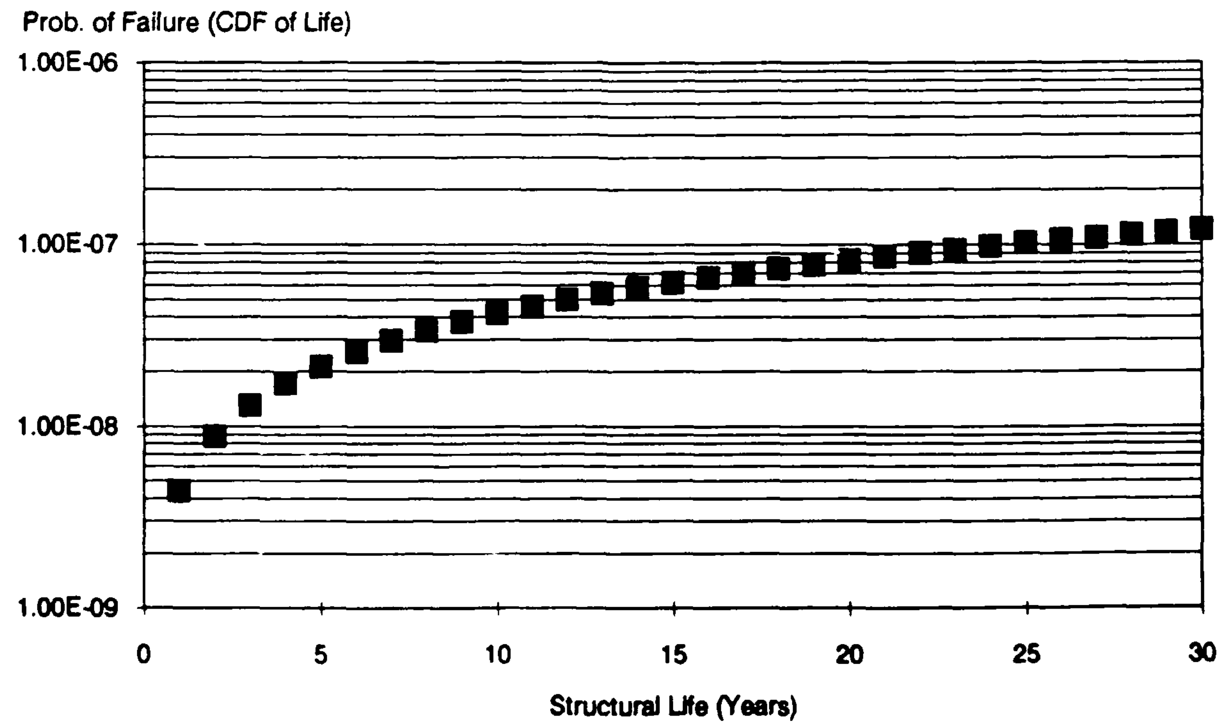

Figure 8-2. Structural Life Expectancy Based on Fatigue for the Island-Class

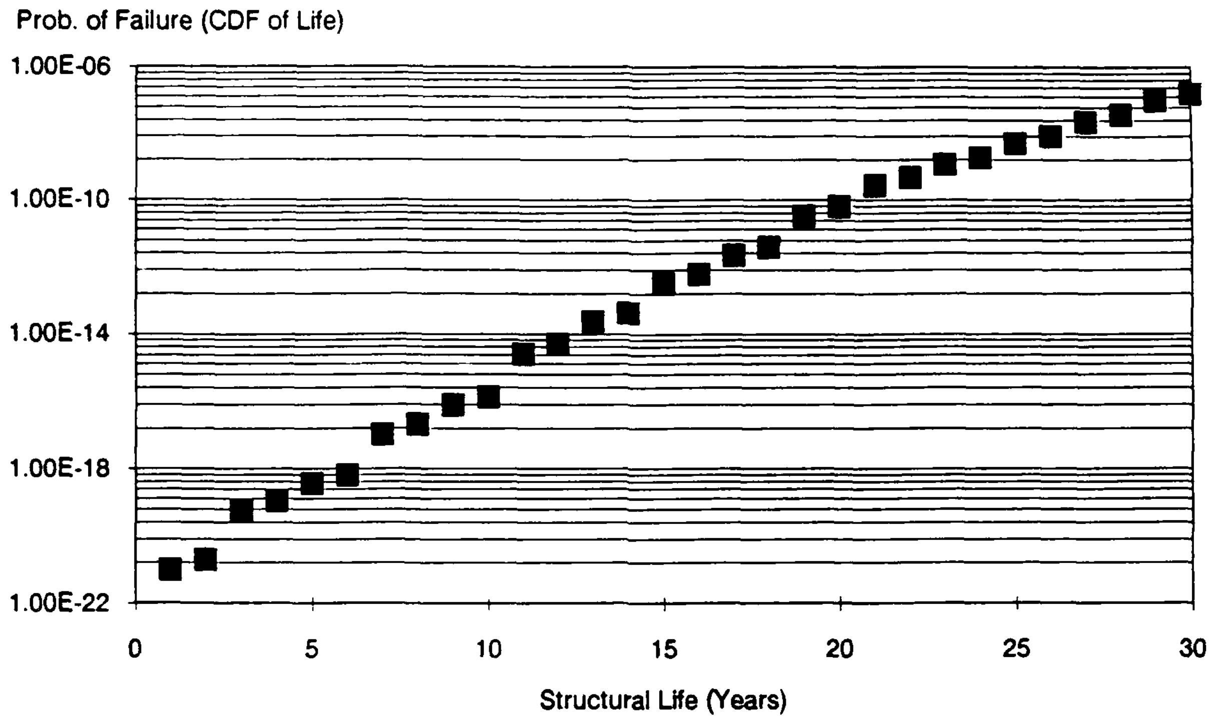

Figure 8-3. Structural Life Expectancy Based on Plate Deformation for the Heritage-Class

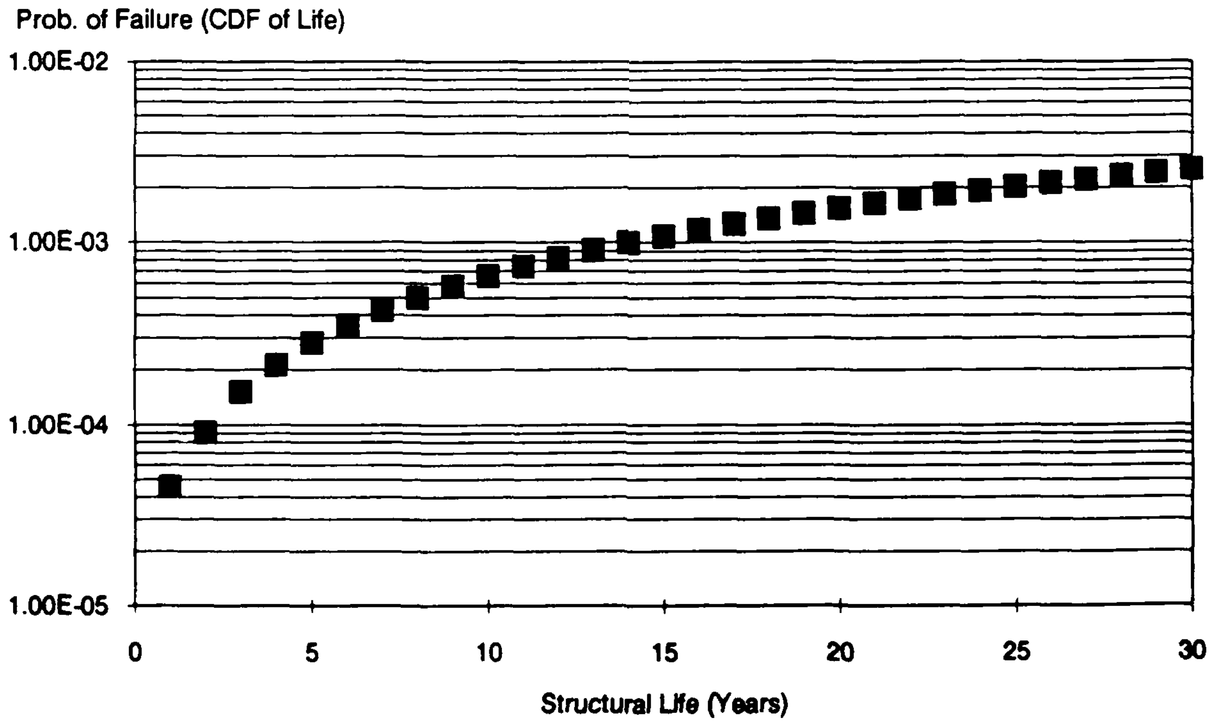

Figure 8-4. Structural Life Expectancy Based on Fatigue for the Heritage-Class

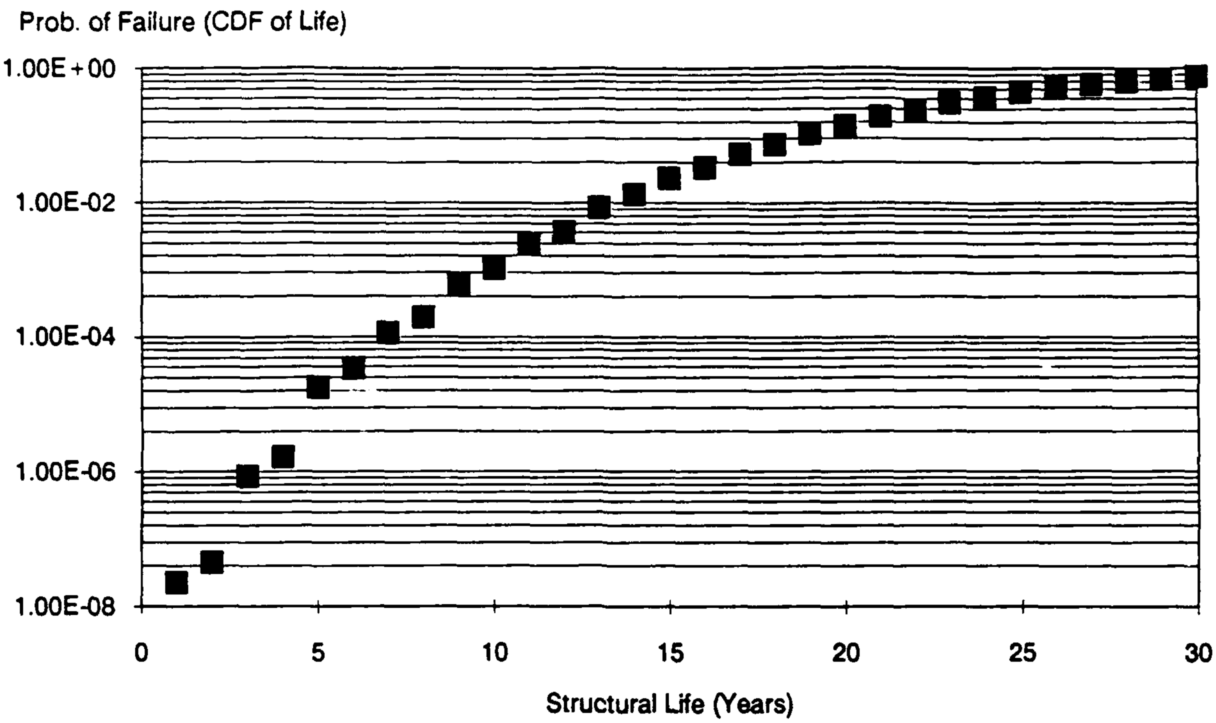

Figure 8-5. Structural Life Expectancy for the Island-Class (Combined Plate Deformation and Fatigue Modes)

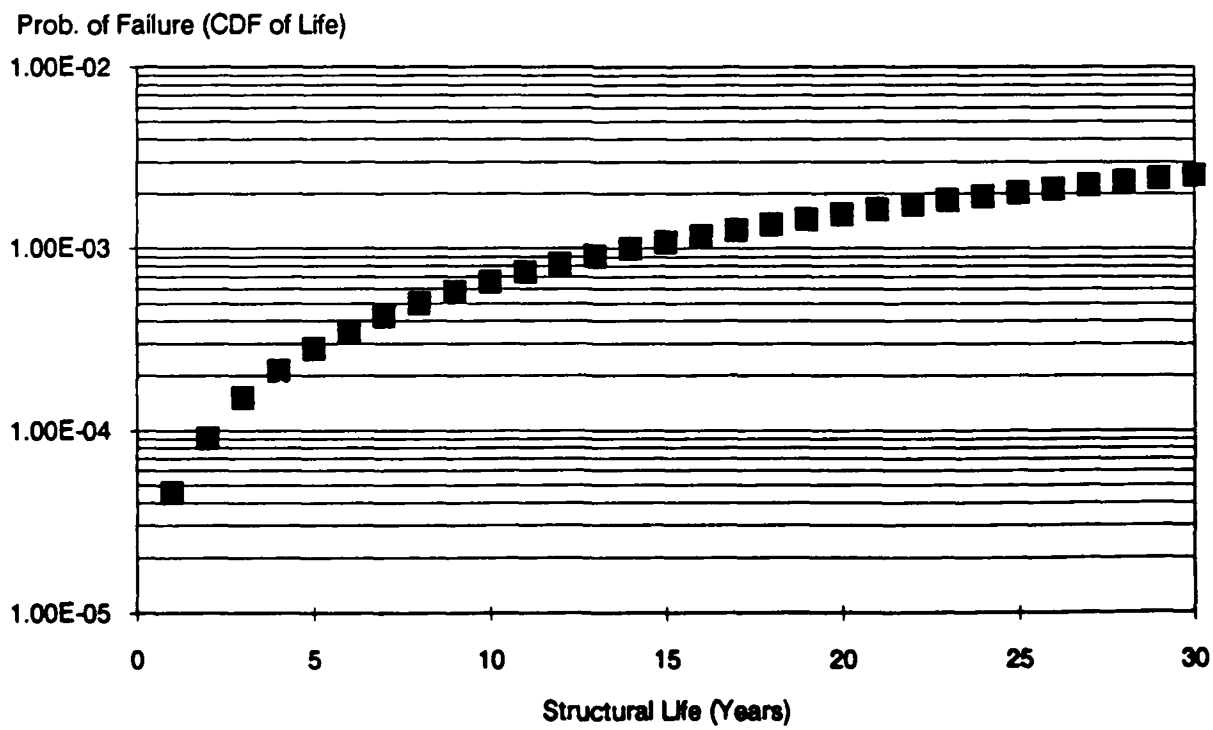

Figure 8-6. Structural Life Expectancy for the Heritage-Class (Combined Plate Deformation and Fatigue Modes)

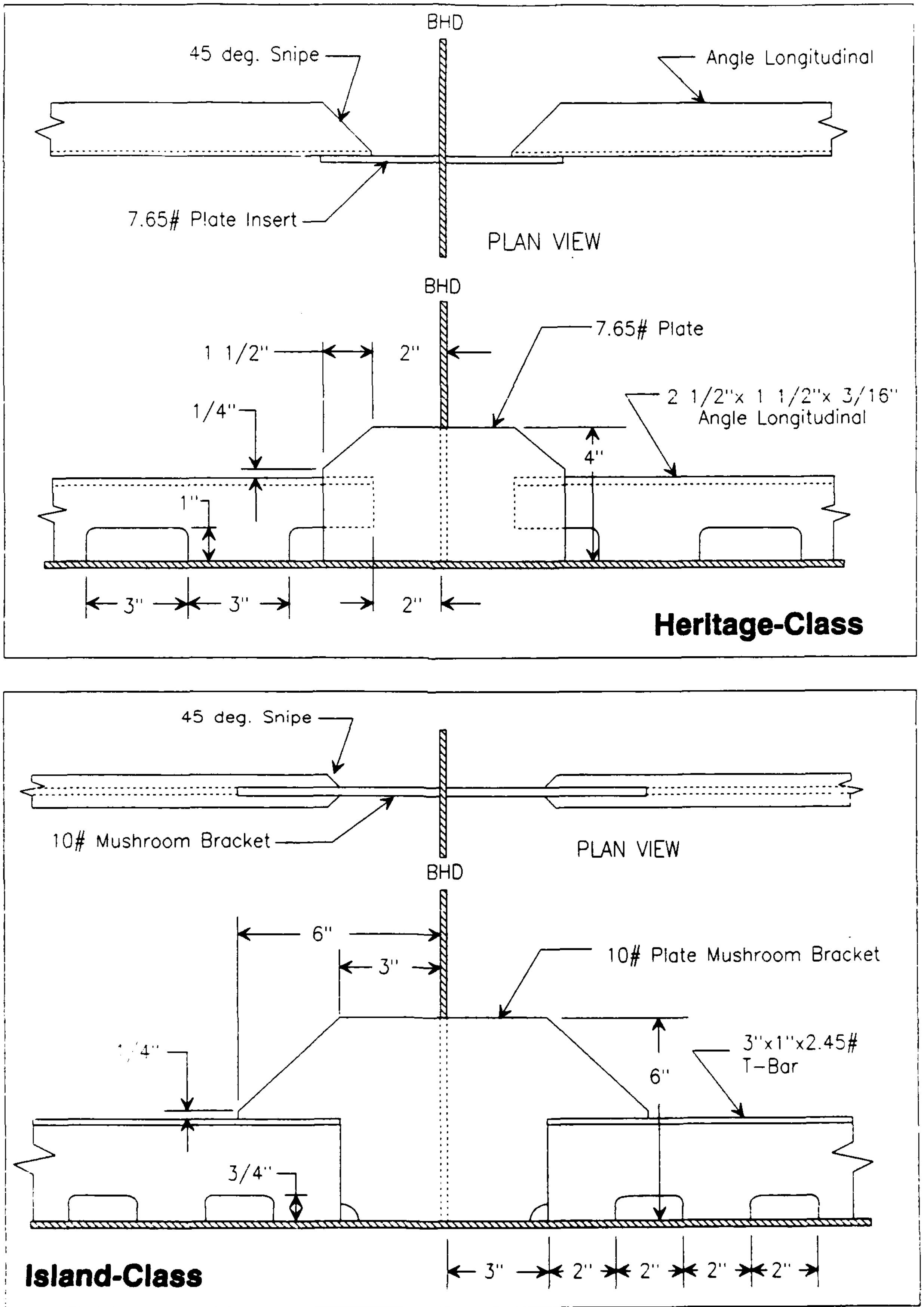

Figure 8-7. Longitudinal Details-Island and Heritage Classes

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9. PARAMETRIC ANALYSIS

9.1 DEFINITION OF PARAMETERS

A parametric sensitivity analysis of the developed analytical model was performed on the Island-Class patrol boat. In order to perform the analysis, a reference set of values for the analytical model parameters needs to be defined. This set is used to assign values for all the parameters except the parameter being investigated. The value of the parameter under investigation is varied to cover a selected range, and the variation of the estimated structural life expectancy according to the two failure modes due to this parametric variation is plotted. The reference set is selected such that all the parameters are at the normal levels of the strength, loading and operational profile characteristics. The reference set of parameters was previously defined as shown in Table 7-1.

The parameters that are considered in this sensitivity analysis include the simulation cycles, size of the plating panel, thickness of the plating, operational profile, number of operational hours per year, loading profile, fatigue details, and plate failure criteria. The selected parameters are summarized in Table 9-1. The sensitivity of the structural life expectancy of the forward bottom plating to variations in these parameters was evaluated. The evaluation was performed for both the plastic plate deformation and fatigue failure modes. The treatment and presentation of the two failure modes were maintained separate in order to keep track of the sensitivity of each failure mode to the variation in the parametric values. The resulting probabilities of failure as a function of time are summarized in figures that correspond to the reference case and the cases with each varied parameter.

9.2 RESULTS

In this section, the results of the parametric analysis are summarized. A brief discussion of the results is provided. These results can be used by the U.S. Coast Guard to study the effects of future design changes. For other parametric variations that are not considered in this section, the developed computer program as shown in Appendix C can be used to generate the needed results. A similar parametric analysis can be developed for other boats by the U.S. Coast Guard using the provided computer program.

9.2.1 Simulation Cycles:

In order to select the least number of simulation cycles that gives results with acceptable levels of statistical accuracy, the resulting failure probabilities for the analytical model were determined as a function of the number of simulation cycles. The statistical accuracy is measured in terms of the convergence of the estimated probability of failure and the magnitude of its coefficient of variation (COV). The results are shown for both the plate deformation and fatigue failure modes

in Figures 9-1 to 9-4. The selected numbers of simulation cycle is based on satisfying the convergence criterion and maintaining a level of COV less that 0.1. By inspecting the resulting figures, 2000 simulation cycles and 500 simulation cycles for plastic plate deformation and fatigue failure modes, respectively, yield in statistically accurate results. Therefore, these numbers of simulation cycle were selected and used in all the program runs in this study.

9.2.2 Plate Thickness:

The plate thickness of the forward bottom plating of the Island-Class patrol boat was varied from its current value of 0.161 in (7#) plate to 0.171 in (7.5#), 0.224 in (9#) and 0.236 in (10#) plate sizes. The resulting probabilities of failure for the plastic plate deformation failure mode are shown in Figure 9-5. Based on these results, the structural life expectancy of the forward bottom plating of the Island-Class patrol boat in this critical failure mode can significantly be improved by increasing the plate thickness to 7.5# or 9#. The effect of plate thickness variation on fatigue life expectancy of the critical region is minimal, therefore, was not considered.

9.2.3 Plate Aspect Ratio:

The current aspect ratio of a plate in the forward bottom part of the boat is 2. This aspect ratio is based on the plate size, length x width, of 23.5 in x 11.75 in. In this analysis, the aspect ratio was changed to 1, which corresponds to change in the plate size to 11.75 in x 11.75 in. The resulting probabilities of failure in the plastic plate deformation for both plate sizes are shown in Figure 9-6. Therefore, structural life expectancy of the forward bottom plating of the Island-Class patrol boat in this critical failure mode can significantly be improved by reducing the plate size. It is evident that this approach is more effective than increasing the plate thickness. The effect of this change on fatigue is in the form of increasing the number of fatigue details. However, since the failures of fatigue detail are considered to be statistically highly correlated, the effect of this change on fatigue life expectancy is minimal.

9.2.4 Rate of Plate Wastage:

The probabilities of failure in plastic plate deformation were estimated for a mean value of wastage rate of 0, 1, 1.5 and 2 mpy. The results are summarized in Figure 9-7. Unquestionably, the inclusion of a wastage allowance in the structural life expectancy model is vital for a realistic prediction of life. However, the model is slightly sensitive to the selection of the plate wastage rate within the range 1 to 2 mpy. In this study, a wastage rate of 1 mpy was used.

The effect of plate wastage on fatigue life expectancy is in the form of slightly shifting the location of the neutral axis of the cross section at the fatigue details. The effect of this neutral axis location change on the structural life expectancy of fatigue details is relatively small. It can be shown that after 30 years with a plate wastage rate of 1 mpy, this

effect results in detail-stress transfer function values that are 10 to 20% less than the case of no wastage allowance.

9.2.5 Annual Use:

The current average annual use of the Island-Class patrol boat is 2167 hours/year. The effect of varying this usage on the probabilities of failure in plastic plate deformation and fatigue are shown in Figures 9-8 and 9-9, respectively. These results are based on varying the annual use from 2167 to 1500 and 3000 hours/year. The effect of increasing the annual use of a boat is greater on fatigue than plastic plate deformation structural life expectancy. However, the analytical model is slightly sensitive to the selection of the average value of annual use.

9.2.6 Plate Failure Criteria:

The plate failure criteria are defined by mainly two parameters, the deformation ratio w_p/t_h and the total number of failed plates within the critical region n_p/N_p. The effect of variation in these parameters on structural life expectancy is studied in this section.

a. Deformation Ratio. The deformation ratio w_p/t_h for the Island-Class patrol boat was selected to take the value of at least 3, as shown in the reference case of Table 7-1. The effect of varying this ratio on the probability of failure in plastic plate deformation is shown in Figure 9-10. In this figure, the ratio takes the values of 2.5, 3.0 and 3.5. Evidently, structural life expectancy based on plastic plate deformation is sensitive to variations in this parameter. However, this ratio was carefully selected to take the value 3 in the reference cases for the Island and Heritage-Class patrol boats based on the model calibration process, as described in Section 7.2.

b. Number of Plates. The total number of failed plates within the critical region n_p/N_p for the Island-Class patrol boat was set to take the value of at least 6/28, as shown in the reference case of Table 7-1. The effect of varying this criterion on the probability of failure in plastic plate deformation is shown in Figure 9-11. In this figure, the criterion takes the values of 3/28, 6/28 and 9/28. Evidently, structural life expectancy based on plastic plate deformation is sensitive to this parameter. However, this criterion was carefully selected to take the value 6/28 in the reference case for the Island-Class patrol boat based on the current practices of the U.S. Coast Guard.

9.2.7 Speed/Sea State:

As was previously discussed, case 8 of the speed/sea state combinations represents the most critical case of the operational profile. This case corresponds to the medium speed and high sea state. It results in significant values for the probabilities of failure in plastic plate deformation. For other speed/sea state combinations, the resulting probabilities of failure are insignificant; virtually zero.

9.2.8 Percent Use in Speed/ Sea State Case 8:

The effect of varying the percent use in the speed/sea state combination that corresponds to case 8 on the probabilities of failure in plastic plate deformation is shown in Figure 9-12. This case corresponds to the medium speed and high sea state. The percent use is considered to take the values 0.5, 1, 1.5 %. Evidently, structural life expectancy based on plastic plate deformation is moderately sensitive to variations in this parameter. The magnitude of this parameter was selected based on a survey that was sent to operators of the Island and Cape-Class patrol boats.

9.2.9 Fatigue Loading Cycles:

Based on the study performed by Ayyub and White in 1988 on the Island-Class patrol boat, the number of fatigue loading cycles was determined to be on the average 1402 cycles/hour based on the strain time-history records. The effect of varying this number on the probabilities of failure in fatigue is shown in Figure 9-13. The loading cycles in this figure are 1200, 1402, 1600 and 1800 cycles/hour. Clearly, structural life expectancy based on fatigue is slightly sensitive to variations in this parameter.

9.2.10 Fatigue Local Details:

According to this study and other previous studies (Ayyub and White, 1988), fatigue local detail 36 was determined to be the most critical one in the forward bottom plating of the Island-Class patrol boat. The effect of eliminating this detail and using in its place local fatigue detail 4 in the form of a continuous weld between the longitudinals and the shell on the structural life expectancy in fatigue is shown in Figure 9-14. Obviously, structural life expectancy based on fatigue can be greatly improved by using local fatigue detail 4 in place of local fatigue detail 36.

Table 9.1 Definition of Parameters for Failure Modes

Parameter	Deformation	Fatigue	Figure No.
Simulation Cycles	x	x	9.1 to 9.4
Plate Thickness	x		9.5
Plate Size	x		9.6
Wastage	x		9.7
Annual Use	x	x	9.8 & 9.9
Plate Failure Criteria			
Deformation Ratio	x		9-10
Number of Failed Plates	x		9-11
Speed/Sea State Cases	x		
Percent Use in Case 8	x	x	9-12
Fatigue Loading Cycles		x	9-13
Fatigue Local Detail		x	9-14

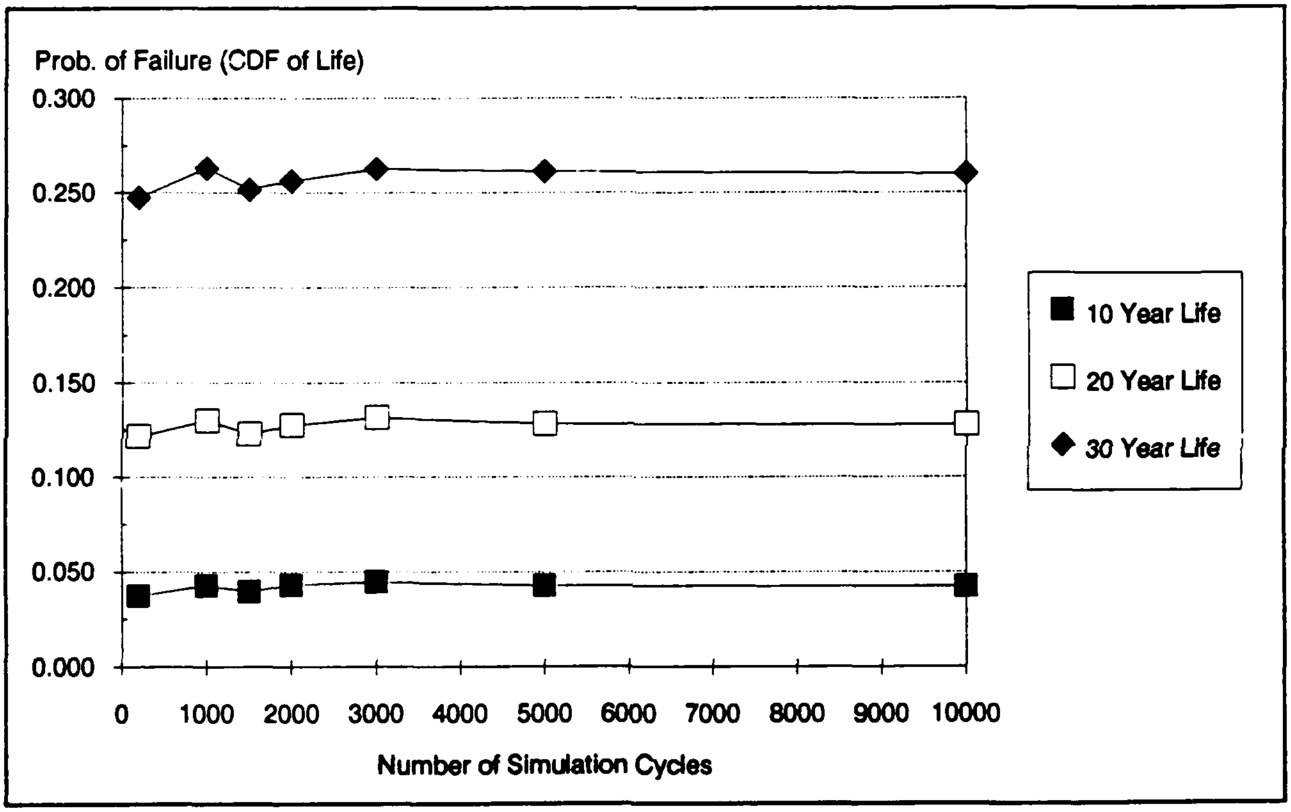


Figure 9-1. Effect of Number of Simulation Cycles on P_f, Plastic Plate Deformation for Island-Class Boat

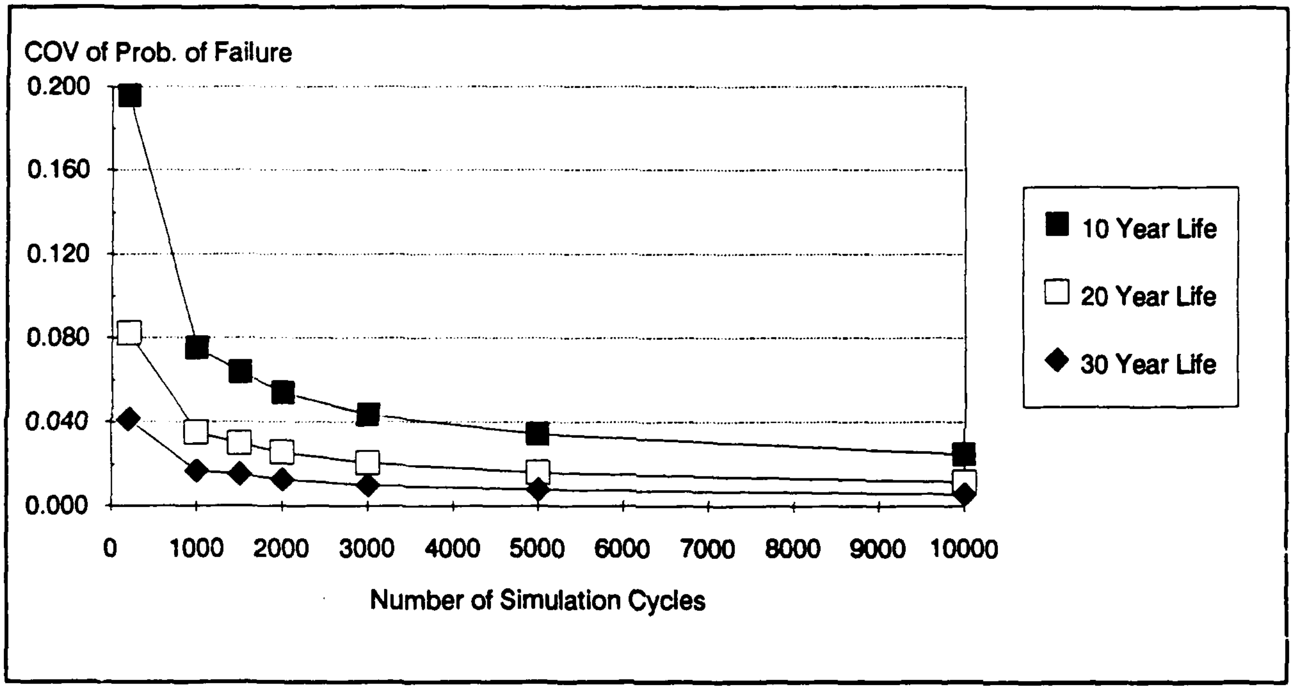


Figure 9-2. Effect of Number of Simulation Cycles on COV(P_f), Plastic Plate Deformation for Island-Class Boat

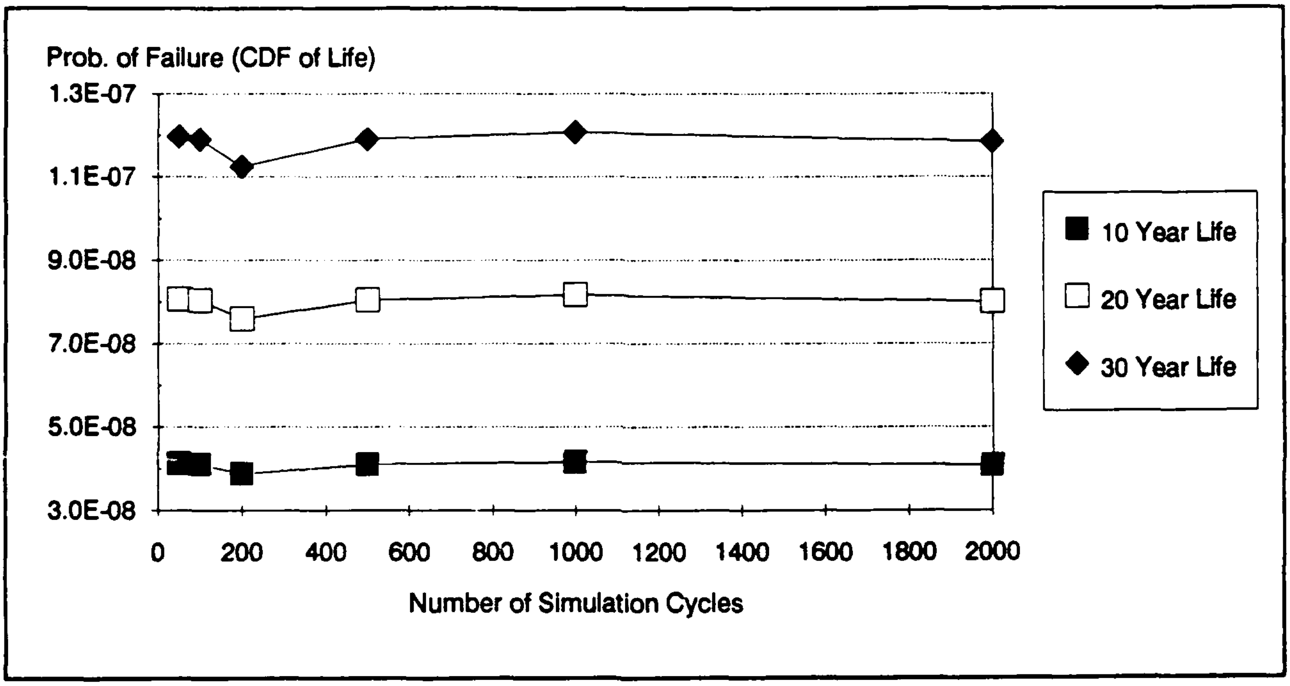


Figure 9-3. Effect of Number of Simulation Cycles on P_f, Fatigue for Island-Class Boat

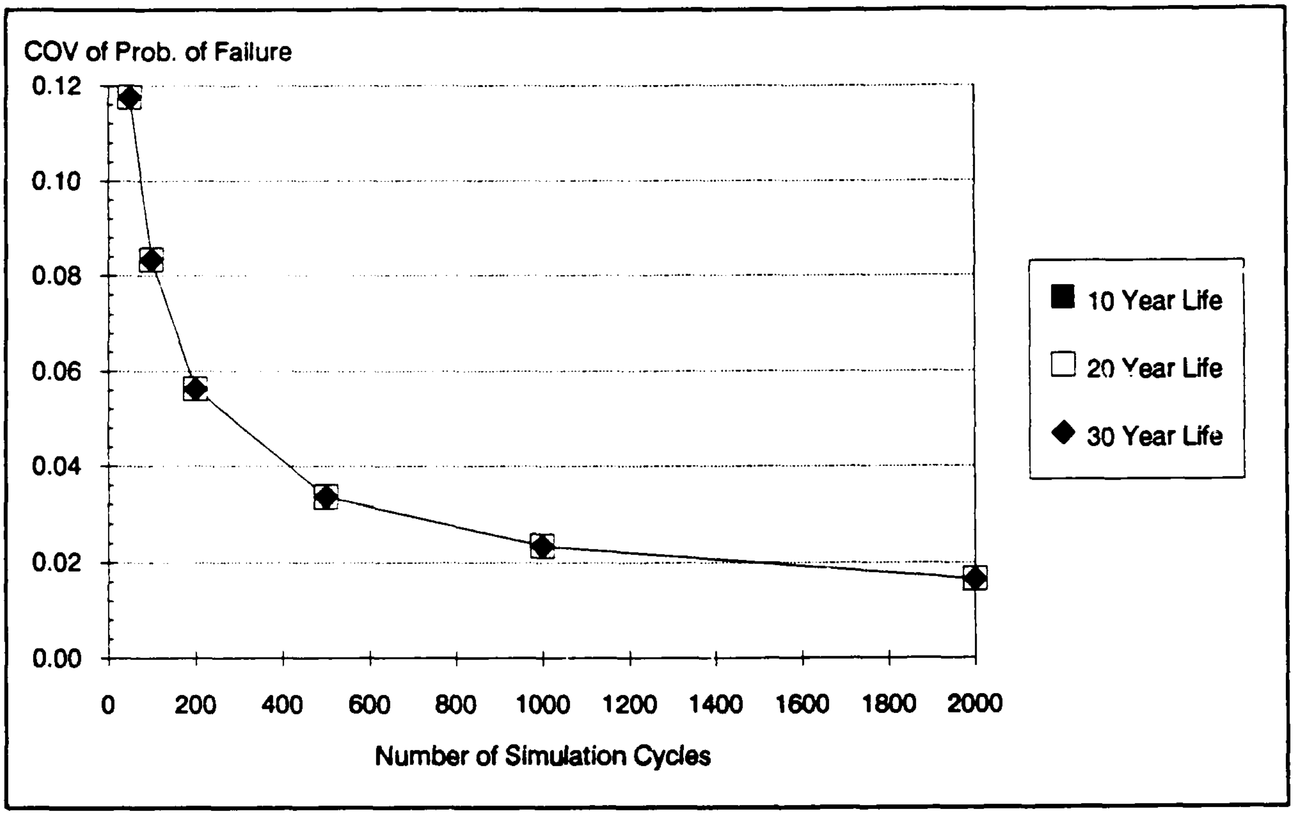
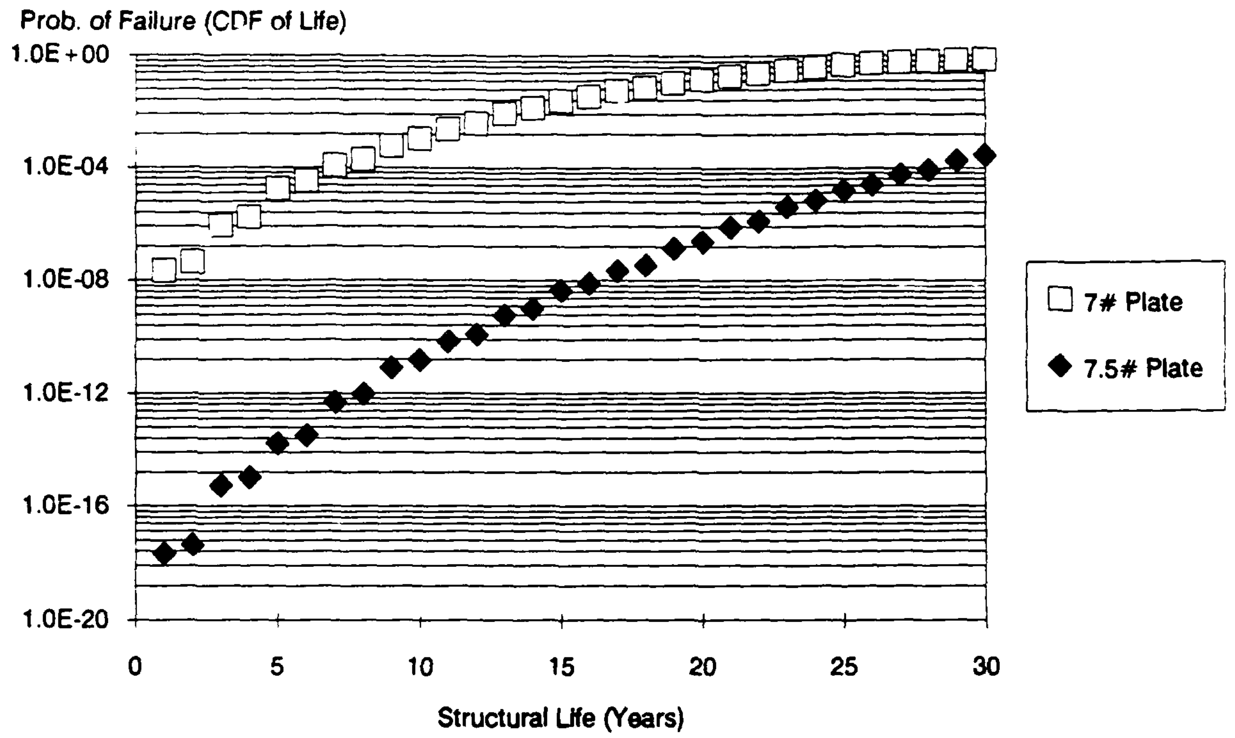


Figure 9-4. Effect of Number of Simulation Cycles on COV(P_f), Fatigue for Island-Class Boat



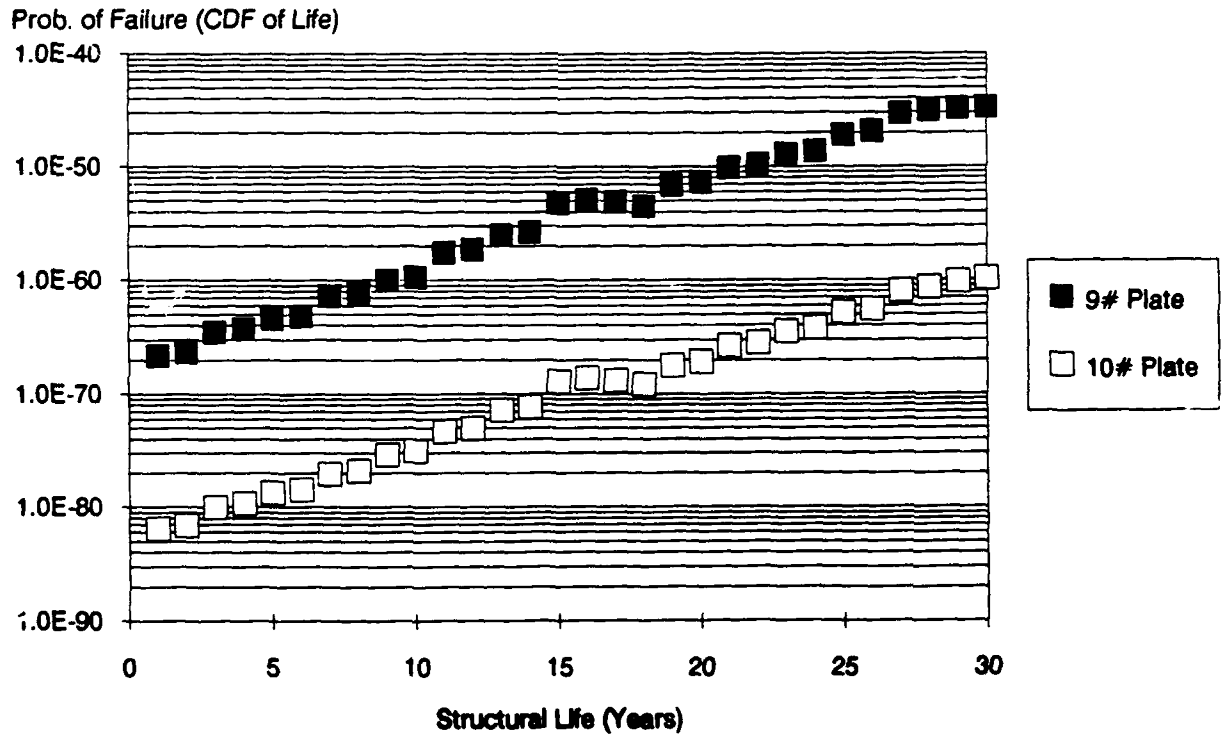


Figure 9-5. Effect of Plate Thickness on P_f, Plastic Plate Deformation for Island-Class Boat

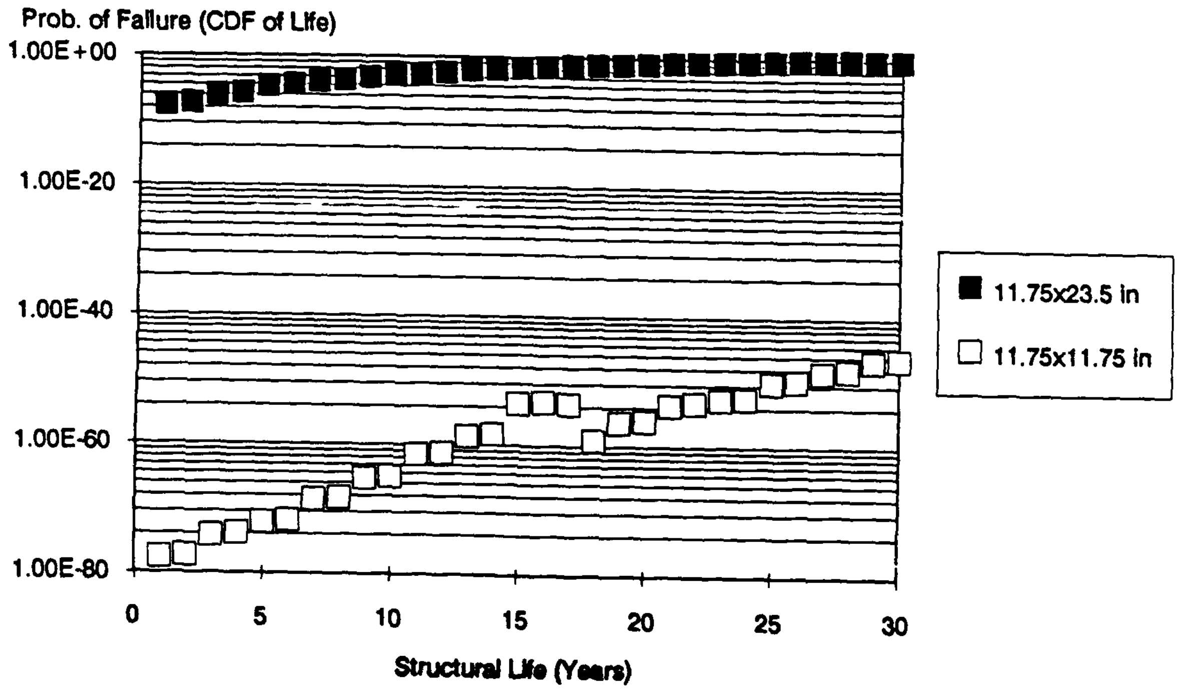


Figure 9-6. Effect of Panel Size on P_f, Plastic Plate Deformation for Island-Class Boat

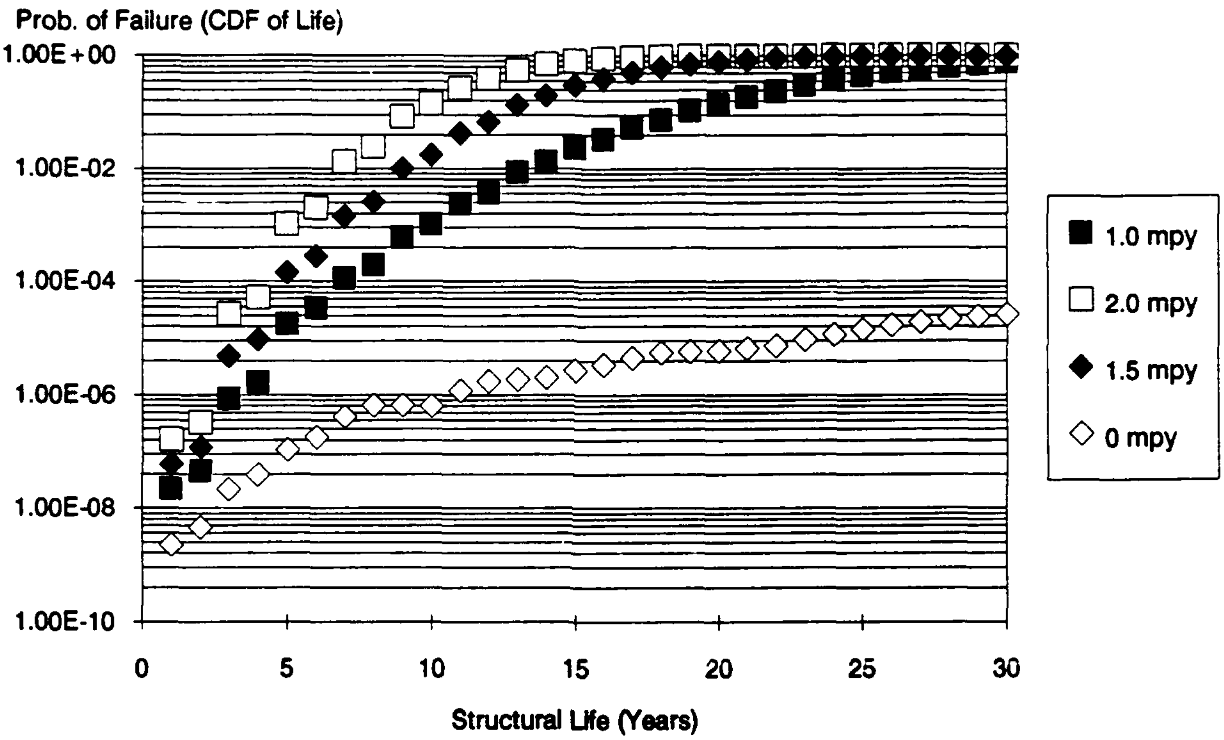


Figure 9-7. Effect of Plate Wastage Rate on P_f,
Plastic Plate Deformation for Island-Class Boat

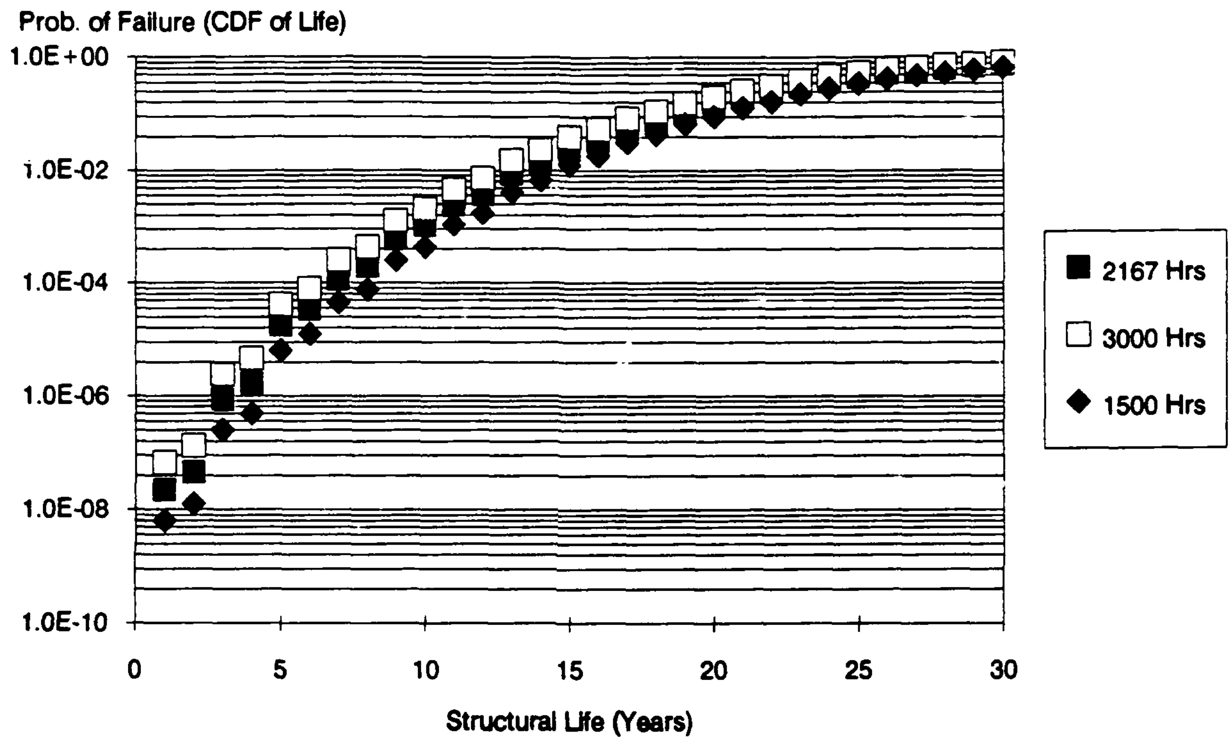


Figure 9-8. Effect of Annual Boat Use on P_f, Plastic Plate Deformation for Island-Class Boat

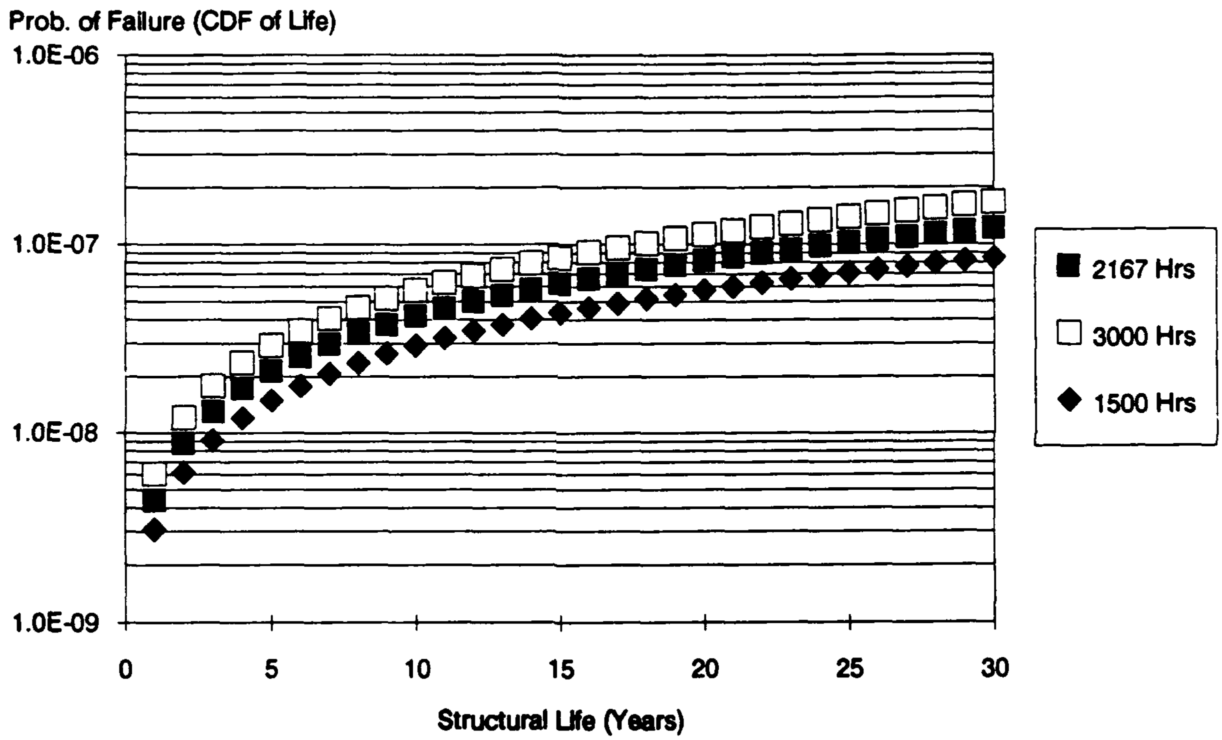


Figure 9-9. Effect of Annual Boat Use on P_f, Fatigue for Island-Class Boat

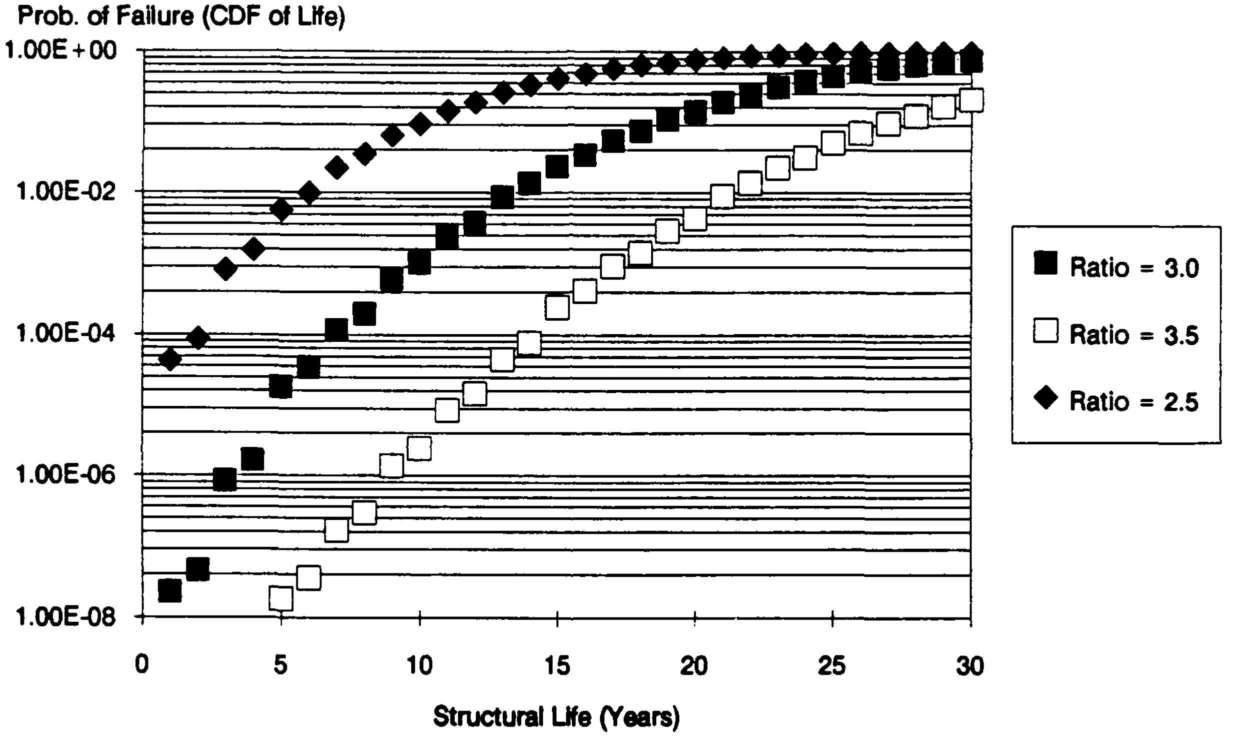


Figure 9-10. Effect of Deformation Ratio on P_f, Plastic Plate Deformation for Island-Class Boat

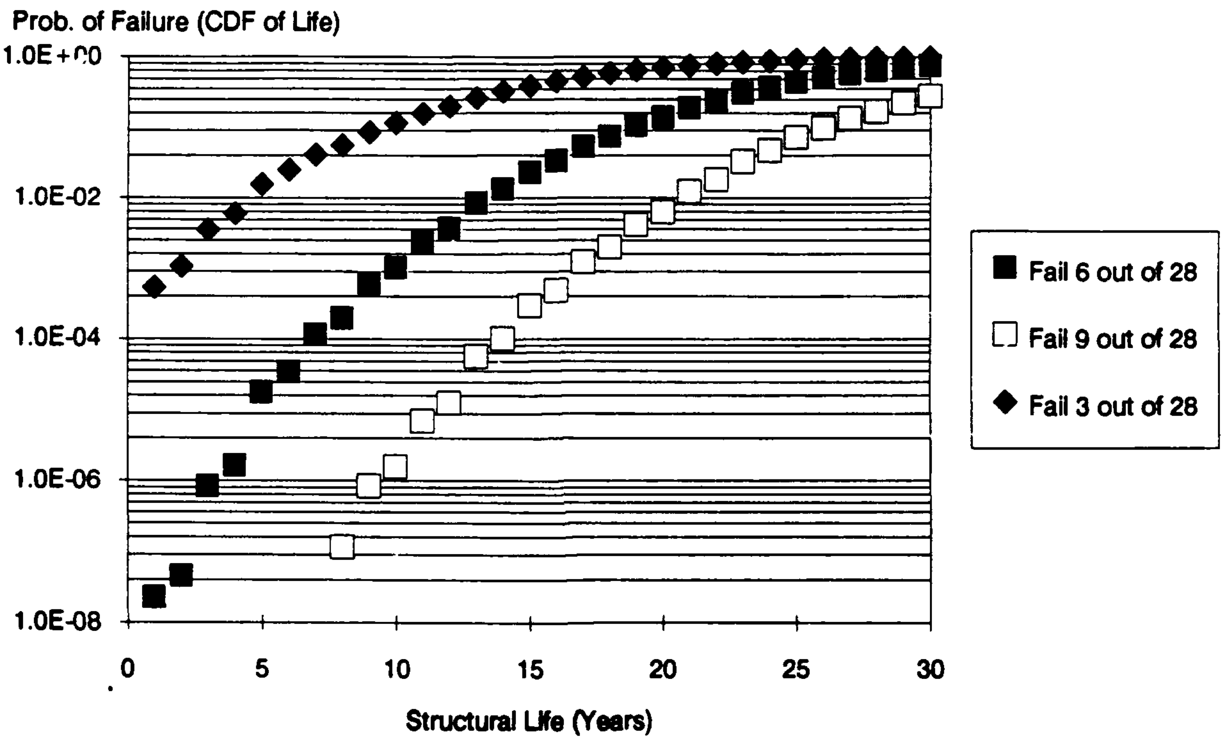


Figure 9-11. Effect of Number of Failed Plates on P_f, Plastic Plate Deformation for Island-Class Boat

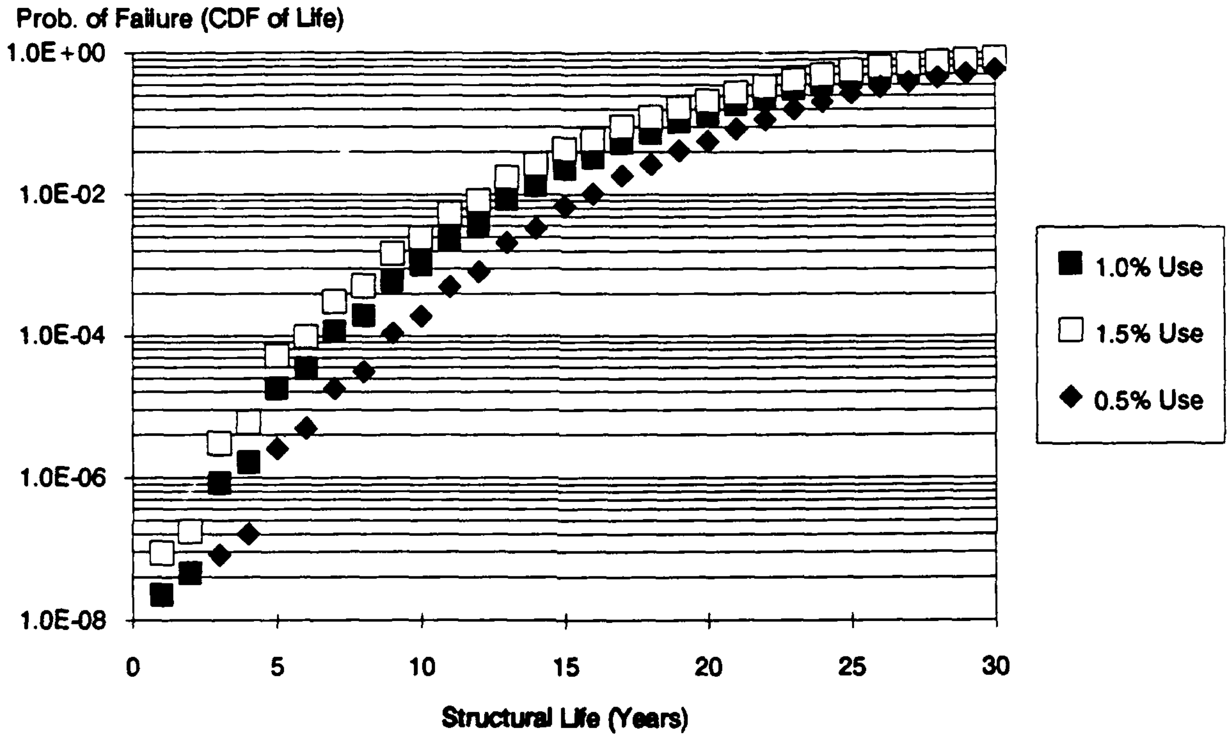


Figure 9-12. Effect of percent Use in Case 8 on P_f, Plastic Plate Deformation for Island-Class Boat

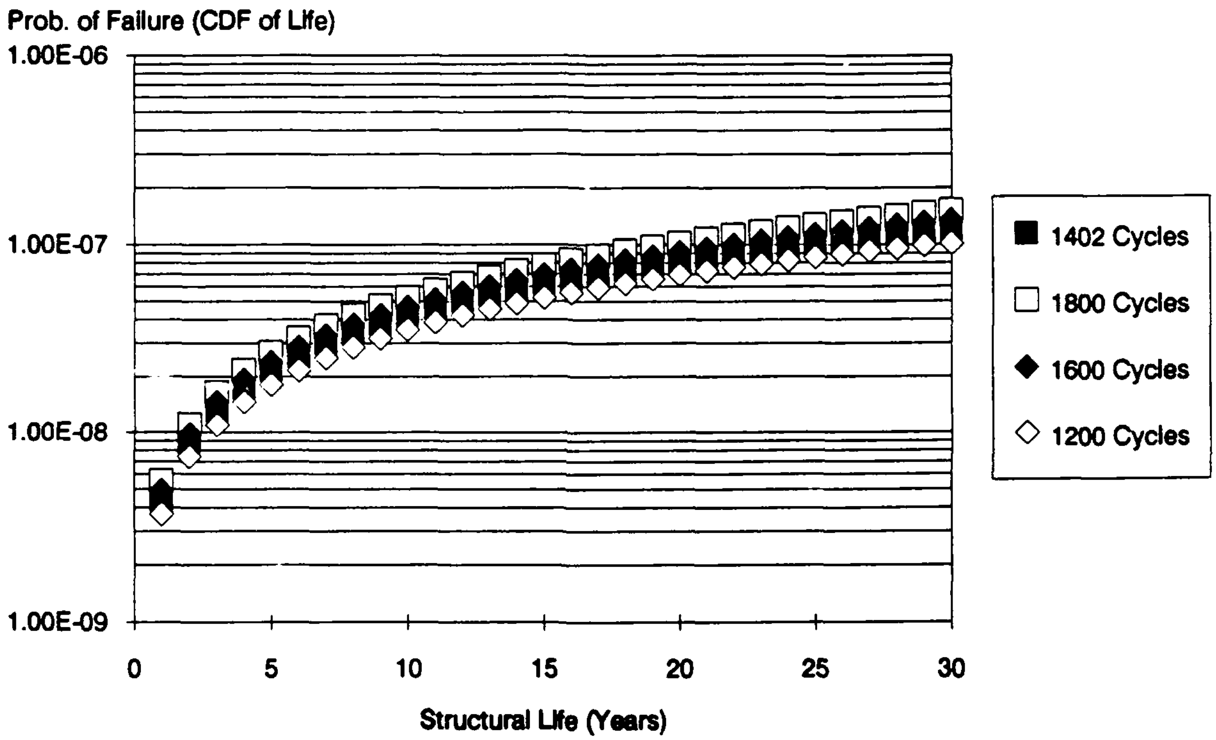


Figure 9-13. Effect of Fatigue Loading Cycles on P_f, Fatigue for Island-Class Boat

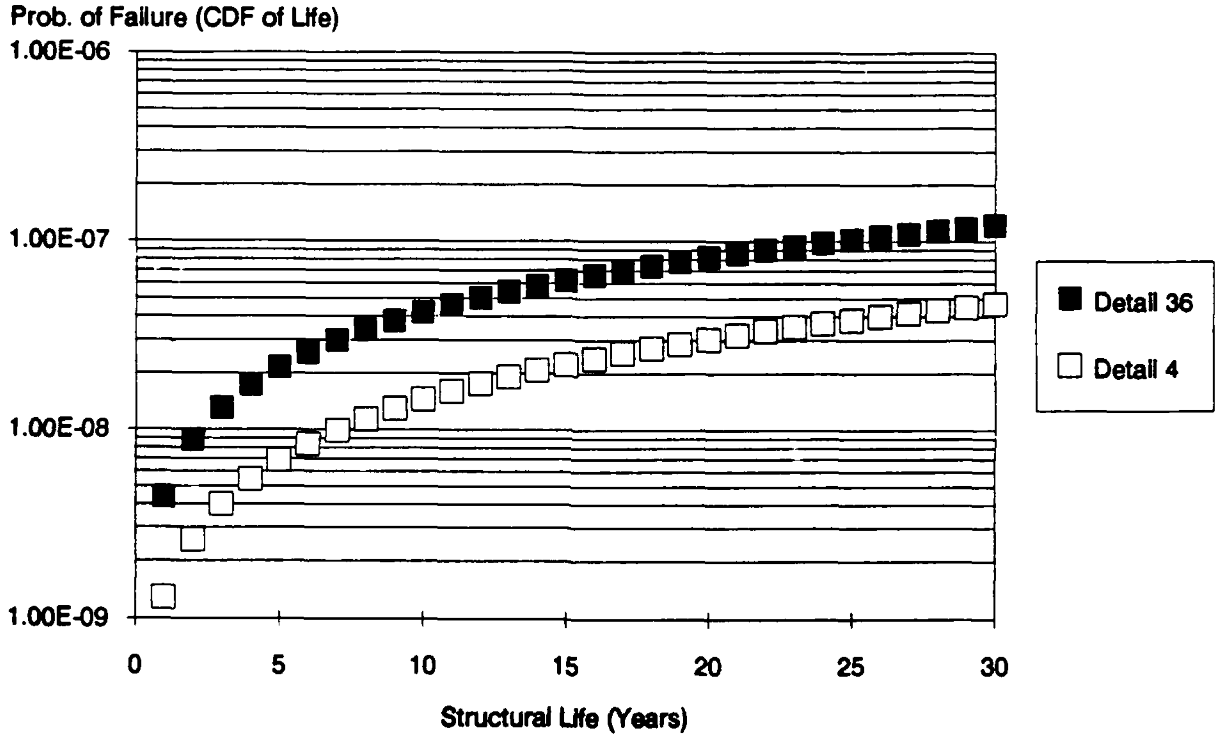


Figure 9-14. Effect of Local Fatigue Detail on P_f, Fatigue for Island-Class Boat

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

A methodology for life expectancy assessment of hull structures was developed, and used for the life expectancy analysis of the forward bottom plating of three of the U.S. Coast Guard patrol boats, the Cape (95 ft), Island (110 ft) and Heritage (120 ft)-Class patrol boats. The developed analytical model was calibrated using reported structural performance information of the Cape-Class patrol boat. The calibrated model was then used for the comparative analysis of the forward bottom plating of the Island and Heritage-Class patrol boats. A parametric sensitivity analysis of the developed analytical model was performed using several variables on the Island-Class patrol boat, to determine which variables have the greatest effect on structural life.

Based on the comparative and parametric analysis, the following major conclusions were reached:

1. The structural life of the forward bottom plating in the plate deformation failure mode can be improved more effectively by intercostal stiffening than by a plate thickness increase. Weight changes for both alternatives need to be determined.
2. A wastage allowance must be included in the structural life expectancy model in order to obtain realistic predictions. However, the model is slightly sensitive to the selection of the plate wastage rate within the range 1 to 2 mpy.
3. Structural life is slightly sensitive to variations in the annual hours of operation. However, if heavy slamming could be avoided, annual hours would have no effect on either plate deformation or fatigue failure modes. Similar results were found for the variable, "Percent Use in Cell 8, medium speed and high sea state."
4. Structural life is sensitive to the selection of the plate "set" ratio, i.e., plate indentation to thickness, and the percent of failed plates within the critical region. A ratio of at least 3 and failed plates of at least 20% were selected, but the selection depends on the amount of plate set and number of damaged panels that can be tolerated in practice.
5. The Island-Class patrol boat life expectancy in the fatigue failure mode was determined to be slightly better than the Heritage-Class patrol boat. Generally, one or more structural details have major effects on this result, therefore, alternative details should be investigated for possible improvement of structural life. The probabilities of failure in fatigue for both boats were within the acceptable limits.
6. The Heritage-Class patrol boat life expectancy in plate deformation failure mode was determined to be significantly better than the Island-Class patrol boat.

10.2 RECOMMENDATIONS

The following recommendations were identified as a result of performing this study:

1. The interactive computer program developed in this study should be used by designers to determine the effects that certain variables have on design pressure and structural life. The methodology can be applied to other types of boats, as well.
2. If more Island-Class patrol boats are going to be built, either the bottom plating should be increased to the 7.5 lb or 9.0 lb level, or intercostals should be used to reduce the size of the plate panels in the forward slamming region. Existing vessels should have the intercostal design incorporated as s Shipalt. Sandblasting of the plating of the Island-Class patrol boat should be avoided, as indicated by the sensitivity of the structural life to the wastage parameter.
3. The structural detail that is the most critical to the Heritage-Class fatigue life is presently used for the intersection of the longitudinals with bulkheads (fatigue detail #26). This detail should be investigated for possible changes with construction and weight considerations.
4. More data need to be collected on slamming pressures, accelerations, plate wastage and operating profiles. Also, bottom plating damage noted during drydocking should be measured, not just observed. The data collection needs to be scientifically conducted on a statistical basis. An effective data collection, storage and retrieval system should be developed. The data collection system should interface and tie well with reliability-based inspection and maintenance procedures.
6. Reliability-based inspection guidelines should be developed that can be used as part of the data collection program. This could offer guidelines for the type and frequency of inspection, critical failure modes and locations, definition of significant damage criteria, corrective actions, and measurements that need to be collected for the reliability methodology.

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APPENDIX A.
LIMIT STATE EQUATIONS

A.1 PLASTIC DEFORMATION OF HULL PLATING

One of the potential failure modes identified for further analysis as a part of this effort is the large plastic deformations which result in hull plating due to wave impact or slamming loads. This mode represents a serviceability *limiting* failure mode rather than an *ultimate* failure mode. The serviceability limiting comes from concerns regarding hydrodynamic performance as a result of a number of bottom plating panels which have large plastic deformations.

A serviceability limit-state of a ship's bottom plating could be the result of either stiffener failure or plating failure. In general, due to the stiffener size required to prevent ultimate failure of the stiffener-plate combination, the plating usually reaches its maximum allowable deformation before the stiffeners have undergone any appreciable plastic deformation. Therefore it should be the plating that is specifically investigated for a serviceability *limiting* condition when considering a panel of plating experiencing a uniform pressure load.

At this point it would be useful to identify and explain some of the assumptions regarding the bottom plating under investigation. For vessels of this size (95 ft to 120 ft LWL) and designed for high speed performance, the longitudinal bending moment of the hull girder is <u>not</u> the dominate loading. Rather the out-of-plane hydrostatic/hydrodynamic pressure exerted on the hull plating drives the design of the structure. While in-plane stresses as a result of longitudinal bending do exist, they are small in comparison to the stresses resulting from out-of-plane pressure. In addition, the area of the hull plating under investigation is near the forward quarter point of the ship, a region where the longitudinal bending moment is much smaller than it is near midships.

There are a number of different approaches for dealing with the inelastic action of plating. Hughes (1981) provided a careful investigation into the suitability of several cases involving a serviceability limiting analysis of plating under uniform pressure loading. Much of the following discussion is based on that work. He concluded that the approach used depends on the following three factors:

1. The magnitude of the allowable permanent set;
2. the duration of the loading: static, quasi-static, dynamic; and
3. the slenderness of the plate, as defined by the following expression of the plate slenderness ratio

$$\beta = \frac{b}{t_h} \left(\frac{F_Y}{E} \right)^{1/2} \qquad \text{(A.1-1)}$$

in which b is the width of the plate, t_h is the thickness of the plate, F_Y is the yield stress and E is the modulus of elasticity.

For the ship and loading under consideration in this study, these three factors are addressed. Firstly, the magnitude of the allowable permanent set. Based on meetings and discussions with US Coast Guard personnel (Ayyub and White, 1988), it was concluded that a permanent set of at least 3.0 times the plating thickness would be considered as unacceptable. This level of permanent set represents, as described earlier, a serviceability limiting limit state. When a panel of plating reaches this level of permanent set, the panel is usually cut out and replaced with new steel. This inspection and replacement usually occur during the vessel's regular maintenance hauling.

Ship plating can generally be divided into two broad categories based on plate slenderness: *slender* plates ($\beta > 2.4$), and *sturdy* plates ($\beta \leq 2.4$). Uniform pressure loaded *sturdy* plates, with a small b/t_h ratio, deflects in relatively small amounts. This is due to the fact that the deflection ratio w_p/t_h is proportional to $(b/t_h)^4$. The principal result of this, when the sturdy plates are experiencing loading, is that membrane effects are quite small, even after yielding has occurred. This indicates that small-deflection elasto-plastic theory is suitable for an analysis of plate serviceability of this type. For *slender* plates, the deflections are relatively larger for a given load and membrane effects are significant. As a result, large deflection theories are required to perform this analysis.

For the plating panels under consideration in this study, the b/t_h ratio is usually around 70, and the slenderness ratio β is approximately 2.5 to 3.0. Such values place these plates in what is considered as the *slender* category and which then requires a large deflection analysis to study these plates. There are two general approaches for large deflection analysis: the rigid-plastic hinge-line method, and an elasto-plastic method.

The rigid-plastic hinge-line method has its roots in civil engineering where it is used in the design of concrete slabs. Its use has been extended to naval architecture (Jones, 1971, 1973 and 1977) and was the basis for the Evans and Wierzbicki (1988) report on "Pressure Calculations on the Island Class Patrol Boat". The method is an approximate one which tends to give non-conservative answers, that is, it tends to over predict the required pressure to cause a specified amount of deformation. This is primarily the result of the assumptions behind the method. The major assumptions, as applied to rectangular plates, are:

* The edges are completely restrained from pulling in, so that at large deflections membrane stresses dominate.
* Elastic deflections are ignored. The material is considered to be rigid-perfectly plastic; zero strain until the yield stress is reached, then unlimited strain at the yield stress.
* The plate is divided into 4 regions by straight-line hinges. As the stress in the hinges reaches yield, a kinematically admissible collapse mechanism is formed.

While this approach has its problems, Hughes (1981) showed that if the deflections are very large ($w_p/t_h > 4$) or if the loading must be considered dynamic, its accuracy would be improved. In the case under investigation, the deflections are going to be limited to $w_p/t_h \leq 3.0$. Whether or not the loading is to be considered dynamic or quasi-static depends on the duration of the pressure pulse, τ_d.

If the duration of the pressure pulse τ_d is small relative to the natural period of vibration of the plate T_p, then the dynamic aspects are important and must be taken into account. It can be shown that the natural period of a clamped elastic plate can be approximated by: (Hughes, 1981)

$$T_p = \frac{\pi b^2}{9} \left(\frac{3\rho(1-\nu^2)}{E t_h^2} \right)^{1/2} \tag{A.1-2}$$

where,

ρ - mass density of the plate material (lbs sec^2/ft^4)
ν - Poisson's ratio
b - plate width
t_h - plate thickness
E - Young's Modulus for the material

Base on the analysis for the plate panels of the Island Class patrol boat considered in this study, Ayyub and White (1988) determined that T_p = 0.0024 sec. Comparing this value with the estimates for loading duration provided by Evans and Wierzbicki (1988), τ_d = 50 to 500 milli-secs, it is obvious that the slamming loading in this case should be considered to be quasi-static. Similar calculations were also carried out for the Cape and Heritage-Class patrol boats, resulting in natural periods were 0.01 sec and 0.0048 sec, respectively. These values are also much smaller than the smallest estimated loading duration. Consequently, considering the slamming load to be quasi-static is again a reasonable approximation.

When all of this is considered, the most appropriate formulation for investigating allowable permanent set of hull plating for these types of boats is the empirical elasto-plastic approach given by Hughes (1981). Hughes discussed the background of elasto-plastic methods and provided a simple empirical formulation for solving for the load required to cause a specified amount of plastic deformation. The formulation is based on the underlying principles of elasto-plastic analysis and was calibrated to fit the experimental data from a series of experiments conducted by Clarkson (1962). Those experiments measured the deflection of "ship type" panels under uniform lateral pressure. The resulting expression is given as

$$\text{Resistance} = \frac{F_Y^2}{E} \{Q_Y + T(R_w)[\Delta Q_0 + \Delta Q_1 R_w]\} \tag{A.1-3}$$

where

F_Y - is the yield stress of the material

E - is the modulus of elasticity of the material

R_w - ratio of deformation w_p at a given load to deformation at which an edge hinge is formed, w_{p0}

w_{p0} = $0.07\ \beta^2 t_h$

$T(R_w)$ = $[1 - (1-R_w)^3]^{1/3}$ for $R_w \leq 1$

= 1 for $R_w > 1$

$$Q_Y = \frac{2}{\beta^2(1 - \nu + \nu^2)^{1/2}} \left[1 + 0.6 \left(\frac{b}{a} \right)^4 \right] \tag{A.1-4}$$

$$\Delta Q_0 = \frac{1 + 0.5\beta \dfrac{b}{a} \left[1 + \dfrac{b}{a} \left(3.3 - \dfrac{1}{b} \right) \right]}{\beta^2(1 - \nu + \nu^2)^{1/2}} \tag{A.1-5}$$

$$\Delta Q_1 = 0.95 \left[\frac{b}{a} \frac{1}{(\beta)^{1/2}} \right]^{1.5} \tag{A.1-6}$$

The Q_Y term is the load required to cause the initiation of permanent set, that is the initial yield load. The ΔQ_0 term accounts for the curved transition portion of the load deflection curve where full plastic hinges have not yet developed. The first term in equation (A.1-5), that is the $1/(\beta^2(1 - \nu + \nu^2)^{1/2})$, is the increase in load above Q_Y which would cause edge hinges in an infinitely long plate. The remaining terms correct for both the actual plate aspect ratio as well as membrane effects due to compatibility which occurs between adjacent plates of finite aspect ratio. In effect, this causes an increase in plate slenderness. The ΔQ_1 accounts for the fact that even after the edge hinges form, there is still some load carrying capacity in the plate.

This approach, and Clarkson's data, are for the case where the plate edges are free to pull-in. For typical ship structures assuming that there is no restraint on edge pull-in is a good approximation. However, the results of equation (A.1-3) are generally a little conservative; predicting somewhat lower pressures required for a specified permanent set. However, for relatively small permanent set ratios, which is the case interest in this study, the results of equation (A.1-3) are much more accurate than rigid-plastic hinge-line methods.

A.2 FATIGUE

The relationship developed in section 5.2 of this study require the definition of an *equivalent constant amplitude stress range* for the random stress loading experienced by the vessel in order to be able to use an S-N type relationship. The purpose of this section is to provide the background for the transformation shown in equation (5-20) of section

5.2.5. In addition, a section that shows the relationship between the fatigue design procedure proposed by Munse in SSC-318 (1982) and the approach used in section 5.2 of this report is provided. A more thorough comparison of Munse's approach to other fatigue design methods can be found in White and Ayyub (1987).

A.2.1 Palmgren-Miner's Rule and the Equivalent Stress Range Concept

For most real marine structures, the loading does not take the form of a cyclic constant amplitude applied stress. Rather the loading is a random sequence of various amplitude and frequencies which do not repeat themselves. This type of loading can best be expressed as a continuously distributed random variable, FL. The statistics of the variable FL are derived from recorded stress histories or estimated from wave records. The results are usually expressed as a probability density function (PDF) of stress range for each stress or wave height record . However, in order to use the S-N fatigue data, a relationship between the characteristic value of the wave induced random stress and the constant amplitude stress of the S-N curve is needed. This is accomplished by using the Palmgren-Miner hypothesis to find an equivalent constant amplitude stress for the random load distribution.

The Palmgren-Miner's (P-M) cumulative damage hypothesis is based on the concept of strain energy. It states that fatigue failure occurs when the total strain energy due to n cycles of variable amplitude loading is equal to the total strain energy from *N* cycles of constant amplitude loading. This can be written in the following form:

$$D = \sum_{i=1}^{B} \frac{n_i}{N_i} \tag{A.2-1}$$

where
- B - the number of stress range blocks
- n_i - the number of stress cycles in stress block i
- N_i - the number of cycles to failure at constant stress range i
- D - the damage ratio, which equals 1 at failure.

The calculation of the equivalent stress range starts by dividing the random load distribution into a number of narrow stress blocks of width ΔS. In each stress block the fractional number of cycles is $p_S(s_i)\Delta S$. If N is the total number of cycles in the life of the structure, then the number of cycles in the stress block is given by

$$n_i = N\,[p_S(s_i)\Delta S] \tag{A.2-2}$$

Substituting this expression for n_i into the P-M rule, equation (A.2-1) becomes

$$D = \sum_{i=1}^{B} \frac{N\,p_S(s_i)\Delta S}{N_i} \tag{A.2-3}$$

The N_i in the denominator of equation (A.2-3) is the number of cycles to failure at a constant amplitude stress range. Solving the S-N regression equation (5-19) for number of cycles, substituting it into equation (A.2-3), and requiring $\Delta S \leq 0$ gives

$$D = \int_0^\infty \frac{N\, p_S(s)}{C/S^m}\, ds = \frac{N}{C} \int_0^\infty S^m\, p_S(s)\, ds \qquad \text{(A.2-4)}$$

The term in the integral on the right-hand side of equation (A.2-4) is the mean or "expected value" of the stress range raised to the m^{th} power, $E[S^m]$. For a known distribution type this value is relatively easily found. The expression for the total damage due to the random load can then be written as

$$D = \frac{N}{C}\, E[S^m] \qquad \text{(A.2-5)}$$

where

$$\frac{N}{C} = \frac{1}{S_R^{\,m}}$$

If D is assumed to be equal to one, as is often done, then equation (A.2-5) states that the expected value of the random stress range raised to the m^{th} power is equal to the constant amplitude stress range at N cycles raised to the m^{th} power. Thus, an equivalent constant amplitude stress range can be found for a random variable amplitude stress range from:

$$S_{re} = E[S^m]^{1/m} \qquad \text{(A.2-6)}$$

For $m = 2$, this would represent the RMS value of the random load distribution. In the more typical case for steels, where $m \approx 3$, the equivalent constant amplitude stress range would be the root-mean-cubed (RMC) value of the random load.

A.2.2 Munse's Method

The fatigue design approach proposed by Munse in SSC-318 (1982) is based on calculating a "design" stress range, S_{rd}, for fatigue. This stress range is the maximum peak-to-trough stress range expected at the point in question once under the most severe sea state and during the entire life of the structure. Comparing that stress range to the allowable stress for other failure modes indicates the controlling mode of failure. In any case, the design stress, S_{rd}, must be less than or equal to the nominal permissible stress permitted once by the basic design rules.

According to the Munse approach, the design stress range, S_{rd}, is found using the following equation:

$$S_{rd} = S_N\, R_f\, \xi \qquad \text{(A.2-7)}$$

where

S_N - mean value of the constant amplitude stress range at the design life, N_d

R_f - reliability factor

ξ - random load factor

The mean value of the constant amplitude stress range, S_N, is found by entering the S-N curve of the structural detail of interest at the number of cycles expected in the design life, N_d. The probabilistic nature of the design method is introduce by the two factors in equation (A.2-7). In order to understand the probabilistic basis for these factors each is briefly discussed.

The reliability factor, R_f, is meant to account for uncertainties in the fatigue data, workmanship, fabrication, use of the equivalent stress range concept, errors in the predicted load history, and errors in the associated stress analysis. The factor comes from the assumption that fatigue life is a random variable with a *Weibull* distribution and that the probability of survival through N loading cycles, Prob(N), is given by:

$$\mathrm{Prob}(N) = \mathrm{Prob}(N-1)\ [1 - h(N)] \qquad \text{(A.2-8)}$$

where h(N) is the hazard function as defined by Ang and Tang (1983). In essence, equation (A.2-8) says that the probability of survival through N cycles is equal to the probability of survival through N-1 cycles multiplied by one minus the conditional probability of survival in the cycle from N-1 to N, given survival to that point. The advantage of the hazard function is that it is relatively easy to use to derive a relationship between the design life, N_d, and the mean value of fatigue life, n, of a *Weibull* distribution.

$$\frac{n}{N_d} = \frac{\Gamma(1 + u)}{[1 - L_N(N_d)]^u} = T_L \qquad \text{(A.2-9)}$$

where

$\Gamma(.)$ - the gamma function

u - $v_R^{1.08}$

v_R - total COV of resistance from equation (5-19)

$L_N(N_d)$ - desired reliability level that the life n will meet or exceed the design fatigue life Nd

T_L - a fatigue life factor

It is interesting to note what the fatigue life factor actually represents. Equation (A.2-9) states the mean value of fatigue life to be used in the design process is equal to the desired design life, N_d, multiplied by the fatigue life factor T_L. The two most important factors in determining T_L are the desired reliability level, $L_N(.)$, and the COV of the resistance, v_R. The result of equation (A.2-9) is, in effect, a shifting of the *Weibull* distribution of fatigue life to the right such that the area under the PDF curve to the right of N_d is equal to the desired level of reliability, L_N. The value of v_R controls the shape of the distribution, and therefore influences the magnitude of the shift. Figure A-1 illustrates how these factors affect the mean value of fatigue life.

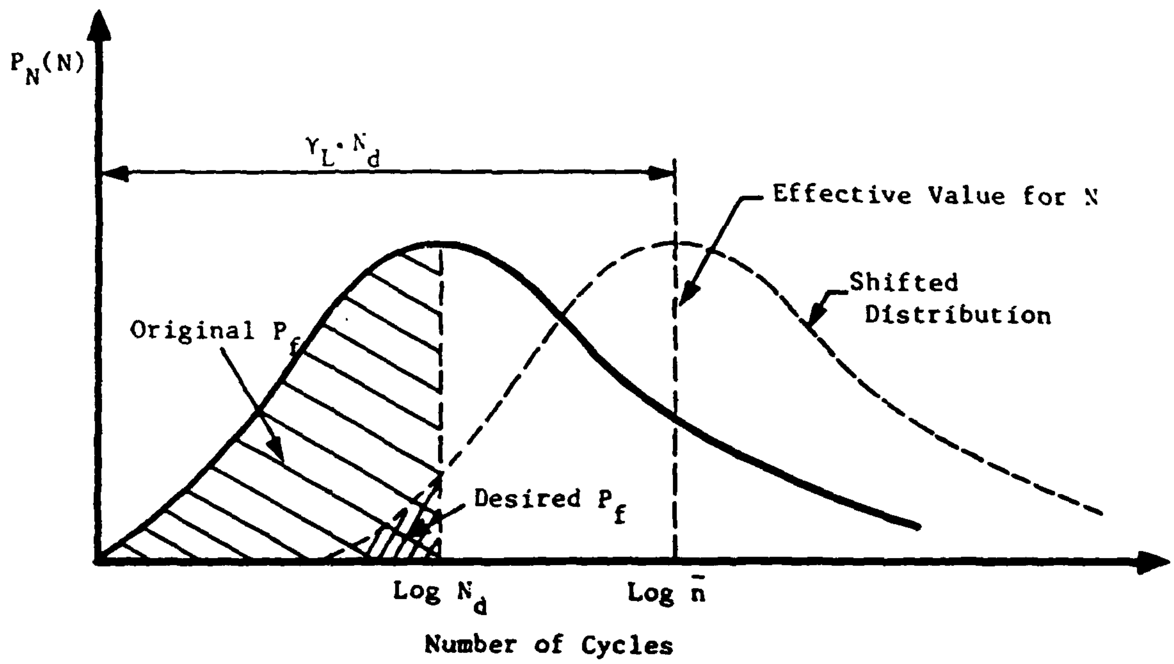

Figure A-1. Effect of Fatigue Life Factor on the PDF of Fatigue Life

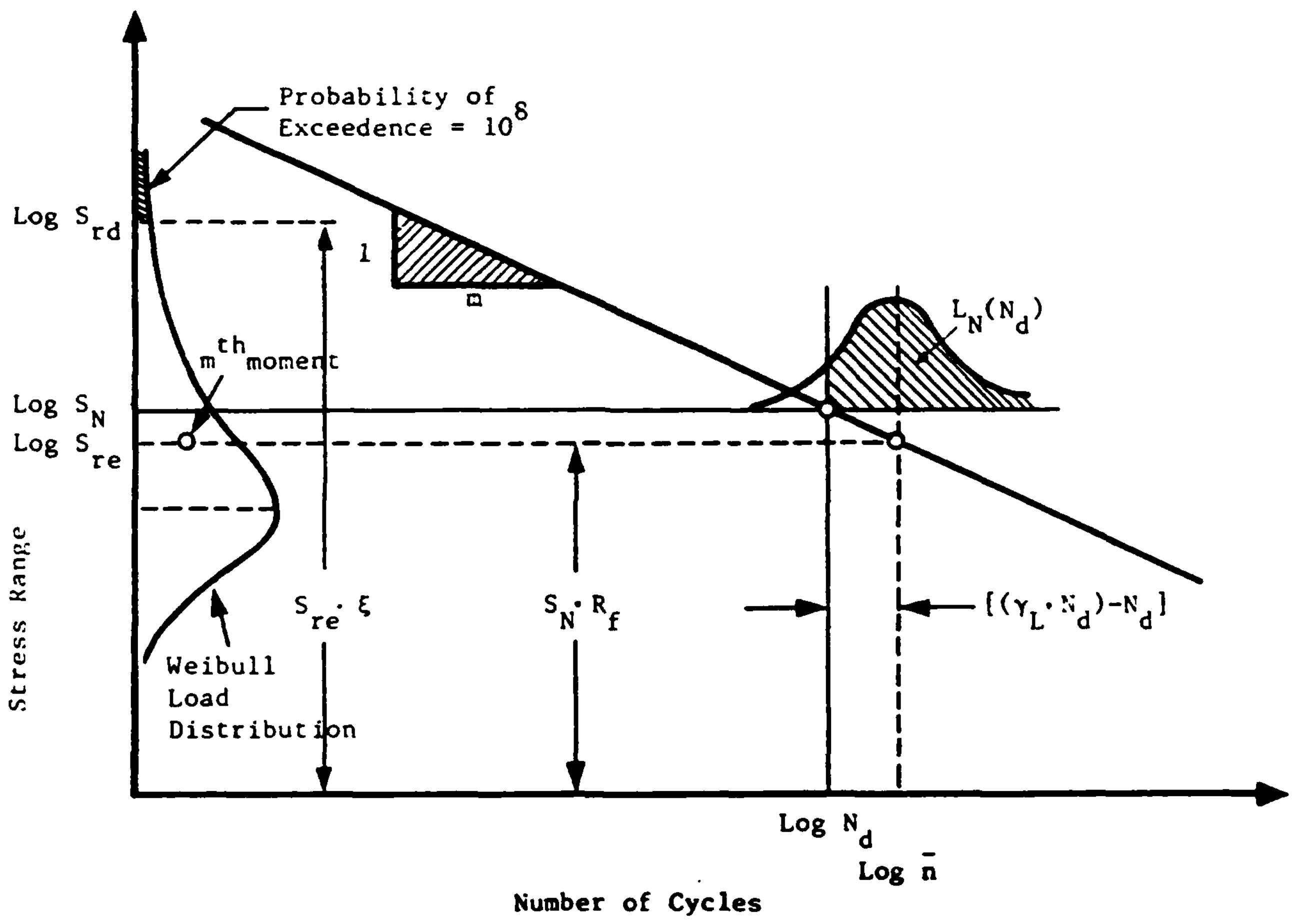

Figure A-2. Graphical Summary of Munse's Method

Then, combining equation (A.2-6) with the value of mean fatigue life from equation (A.2-9) the following expression results:

$$S_{re} = \left(\frac{C}{T_L N_d}\right)^{1/m} = \left(\frac{C}{N_d}\right)^{1/m} \left(\frac{1}{T_L}\right)^{1/m} = S_N R_f \qquad \text{(A.2-10)}$$

where

$S_N = (C/N_d)^{1/m}$

$R_f = (1/T_L)^{1/m}$

It is apparent from equation (A.2-10), that the product of the first two terms of the Munse "design" equation (A.2-7) is an equivalent constant amplitude stress range. The effect of the reliability factor is to reduce the equivalent stress range. The reduced equivalent stress range is equal to that stress range which would be found by using the mean value of fatigue life, n, vice N_d, for calculating the stress range from the S-N curves. This is shown graphically in Figure A-2. Thus, the reliability factor contains a term which has the uncertainty of all of the factors which make up the resistance (v_R), and a term which allows the designer or code writer to specify the desired level of exceedance of the design life ($L_N(N_d)$). The effect of increasing the uncertainty in resistance is a decrease in the reliability factor, and therefore a decrease in the allowable stress. The same effect is achieved by increasing the desired probability of exceedance on design life.

The stress range developed so far by the design procedure is an equivalent constant amplitude stress range based only on the characteristics of the S-N curve. Equation (A.2-6) provides a way to relate this equivalent stress, S_{re}, to the expected loading. From that equation the equivalent stress is equal to m^{th} root of the m^{th} moment of the random load distribution. Since structural elements are designed to extreme loadings, it would be convenient if a design relationship could be introduced to relate the constant amplitude equivalent stress range for the loading to the once in a lifetime extreme stress. Munse achieved this goal by introducing the following:

$$S_{re} = E[S^m]^{1/m} = \frac{S_{rd}}{\xi} \qquad \text{(A.2-11)}$$

where

S_{rd} - the maximum stress range in a random loading expected only once in the vessel's lifetime

ξ - Random Load Factor

$$= \frac{S_{rd}}{E[S^m]^{1/m}}$$

The random load factor represents the distance, along the vertical axis, between the equivalent stress range for the loading, S_{re}, and the "once in a lifetime" stress range S_{rd}. The key to finding the distance is to find the equivalent stress range in terms of the once in a lifetime stress.

APPENDIX B
STRESS TRANSFER FUNCTIONS

Fundamental to the approach used to determine expected life in fatigue is the determination of the stress range to apply to a particular detail. As explained in Section 3.2 of the report, a lifetime stress range histogram was developed from the full-scale test conducted on an Island-Class patrol boat (Purcell, 1988). This histogram was for stress ranges experienced at the center of a plate panel in the defined "critical" region of the boat's bottom. In order to use that information to determine the shape and size of the histogram of stresses for a particular detail, a *transfer function* between stresses at the plate center and that detail is required. In an earlier work (Ayyub and White, 1988), a finite element method (FEM) analysis was used to determine the stress transfer function. Because of the cost of performing an FEM analysis, both in labor and computer time, a different approach was used in this report. The stress level at a point on the detail of interest was determined using basic principles of engineering mechanics for a unit pressure load on the boat bottom structure. The following discussion provides an example of how the calculation was performed. Tables B-1 through B-3 are summaries of the spreadsheet used to calculate stress ratios (transfer functions) for each of the critical details for each boat.

EXAMPLE STRESS RATIO CALCULATION: ISLAND-CLASS DETAIL #25

Detail #25 is the weld which connects the 2"by 2" clip to the 3"x 1"x2.45# T longitudinal at the web frame cutout. A sketch of the detail is provided in Figure B-1. There are twelve of this type of detail in the defined critical region of the boat's bottom.

The first step of the process is to determine the Von Mises equivalent stress in the center of the plate due to a unit uniform pressure loading. Using the procedure described by Ayyub and White (1987), stresses in the X and Y direction at the middle of the plate are found. This involves using Mansour's (1967) coefficients b and g. For the Island-Class plates, using eta - 1.0 ans $N_x/N^* - 0$ because of the small inplane loads, $\beta - 0.004$ and $\gamma - 0.04$. The stresses are found from

$$\sigma_x - 6(pb^2/t_h^2)(\beta + \nu\gamma)$$
$$\sigma_x - 6(pb^2/t_h^2)(\gamma + \nu\beta) \qquad \text{(B-1)}$$

where
- p - uniform pressure loading in psi
- b - plate width in inches
- t_h - plate thickness in inches
- m - Poisson's ratio

For the Island-Class patrol boat the values of σ_x and σ_y are 511.32 and 1316.66 psi, respectively. These values give a Von Mises equivalent stress of 1149.69 psi at the plate center.

The individual 3"x1"x2.45# T longitudinals are treated as fixed-end beams experiencing a uniform distributed load. The fixed-end approximation is a good one for the bottom of ships because each plate panel is similarly loaded, forcing an almost zero-moment condition at the web frames. The beam is made up of the longitudinal and some part of the bottom plating which acts as an effective flange. The amount of bottom plating to include as a flange is called the *effective breadth*. Hughes (1983) discussed this problem at length, and concluded that the effective breadth should be:

$$b_{eff} = 0.577a/3 \quad \text{(B-2)}$$

Here, a is the plate panel length, or the length of the longitudinal between web frames. The 0.577 accounts for the effective length of the fixed-end beam and the 1/3 is used to approximate the effect of shear lag. For the Island-Class, the effective breadth is 4.52 in.

The moment of inertia about the neutral axis of the stiffener-plate combination is found next and is used in the simple elastic flexure formula to find the needed stress

$$\text{Stress} = M\, y/I \quad \text{(B-3)}$$

where
- M - the applied moment on the section of interest.
- I - Moment of Inertia of the combined section about the neutral axis.
- y - the vertical distance from the neutral axis to the point of interest on thesection.

The moment is found using the fixed-end beam formula, for the appropriate location along the length of the beam. The only remaining question is what value to use for y in equation (B-3). The value of y should be chosen to give the maximum tensile stress at the detail weld location. For the case of detail #25 on the Island-Class, y is chosen as 0.397 inches. This is the height of the neutral axis above the plate minus the 0.5 inches from the plate to the bottom of the 2"x2" clip as shown in Figure B-1.

The resulting stress is 112.57 psi. When divided by the Von Mises stress of 1149.69 psi, a ratio of 0.10 is found.

Tables B-1 through B-3 provide the details of the similar calculations carried out for each detail on the three boats being considered in this study.

Table B-1. Detail Stress Transfer Functions for the Island-Class

Fatigue Detail Geometry

	Detail #36	Detail #25	Detail #10A	Detail #4
Flange Width	1.000 in	1.000 in	0.000 in	0.000 in
Flange Thickness	0.189 in	0.189 in	0.000 in	0.000 in
Web Height	2.811 in	2.311 in	6.000 in	12.000 in
Web Thickness	0.189 in	0.189 in	0.250 in	0.112 in
Stiffener Area	0.720 in^2	0.626 in^2	1.500 in^2	1.344 in^2
Stiffener NA height	1.799 in	2.033 in	3.000 in	6.000 in
Inertia of Stiffener	0.664 in^4	0.401 in^4	4.500 in^4	16.128 in^4
Effective Breadth	4.520 in	4.520 in	4.520 in	4.520 in
Combined Section NA	0.854 in	0.897 in	1.994 in	3.864 in
Combined Section INA	1.944 in^4	1.906 in^4	9.151 in^4	33.584 in^4
Pressure Loading	1 psi	1 psi	1 psi	1 psi
Load per in	11.750 lb/in	11.75 lb/in	11.75 lb/in	11.75 lb/in
Max Moment on Section	540.745 in-lbs	540.745 in-lbs	179.432 in-lbs	540.745 in-lbs
Distance from NA to section of interest	0.854 in	0.397 in	1.994 in	3.864 in
Max Stress	237.491 psi	112.570 psi	39.092 psi	62.219 psi
Stress Ratio	0.21	0.10	0.03	0.05

Table B-2a. Detail Stress Transfer Functions for the Heritage-Class

Longitudinal Details

	Detail #36	Detail #20,#21,#39	Detail #26 Section A-A'	Detail #26 Section B-B'
Flange Width	1.500 in	0.000 in	1.500 in	0.188 in
Flange Thickness	0.188 in	0.000 in	0.188 in	1.500 in
Web Height	2.313 in	4.000 in	1.313 in	4.000 in
Web Thickness	0.188 in	0.188 in	0.188 in	0.188 in
Stiffener Area	0.715 in^2	0.750 in^2	1.043 in^2	1.031 in^2
Stiffener NA height	1.648 in	2.000 in	1.719 in	1.932 in
Inertia of Stiffener	0.461 in^4	1.000 in^4	0.556 in^4	1.066 in^4
Effective Breadth	8.078 in	8.078 in	8.076 in	8.078 in
Combined Section NA	0.452 in	0.584 in	0.631 in	0.711 in
Combined Section INA	1.957 in^4	3.231 in^4	2.620 in^4	3.624 in^4
Pressure Loading	1 psi	1 psi	1 psi	1 psi
Load per in	12.000 lb/in	12.000 lb/in	12.000 lb/in	12.000 lb/in
Max Moment on Section	1764.000 in-lbs	1764.000 in-lbs	955.500 in-lbs	1284.000 in-lbs
Distance from NA to section of interest	0.452 in	0.584 in	1.869 in	1.789 in
Max Stress	407.402 psi	319.132 psi	681.692 psi	633.860 psi
Stress Ratio	0.47	0.37	0.79	0.74

Table B-2b. Detail Stress Transfer Functions for the Heritage-Class

Transverse Details

	Detail #51	Detail #28F	Detail #36
Trans. Frame Length	72 in	72 in	72 in
Trans. Flange Width	2.000 in	2.000 in	2.000 in
Trans Flange Thickness	0.188 in	0.188 in	0.188 in
Trans. Web Height	8.000 in	8.000 in	8.000 in
Trans. Web Thickness	0.125 in	0.125 in	0.125 in
Trans. Frame Area	1.375 in^2	1.375 in^2	1.375 in^2
Trans. Frame NA height	5.116 in	5.116 in	5.116 in
Inertia of Trans. Frame	9.905 in^4	9.905 in^4	9.905 in^4
Effective Breadth	13.848 in	13.848 in	13.848 in
Combined Section NA	1.674 in	1.674 in	1.674 in
Combined Section INA	34.586 in^4	34.586 in^4	34.586 in^4
Pressure Loading	1 psi	1 psi	1 psi
Load per in	42.000 lb/in	42.000 lb/in	42.000 lb/in
Shear Force at Section	1008 lbs	N/A	N/A
Avg. Web Shear Stress	1008 psi	N/A	N/A
Max Moment on Section	N/A	9072.000 in-lbs	9072.000 in-lbs
Distance from NA to section of interest	N/A	1.201 in	1.674 in
Max Stress	1008.000 psi	314.932 psi	439.191 psi
Stress Ratio	1.42	[illegible]	[illegible]

Table B-3a. Detail Stress Transfer Functions for the Cape-Class

Fatigue Detail Geometry

	Detail #36	Detail #39	Detail #11
Flange Width	2.281 in	2.281 in	2.281 in
Flange Thickness	0.189 in	0.189 in	0.189 in
Web Height	3.811 in	3.811 in	3.811 in
Web Thickness	0.135 in	0.135 in	0.135 in
Stiffener Area	0.946 in^2	0.946 in^2	0.946 in^2
Stiffener NA height	2.817 in	2.817 in	2.817 in
Inertia of Stiffener	1.562 in^4	1.562 in^4	1.562 in^4
Effective Breadth	13.848 in	13.848 in	13.848 in
Combined Section NA	0.665 in	0.665 in	0.665 in
Combined Section INA	7.501 in^4	7.501 in^4	7.501 in^4
Pressure Loading	1 psi	1 psi	1 psi
Load per in	18.000 lb/in	18.000 lb/in	18.000 lb/in
Max Moment on Section	7776.000 in-lbs	7776.000 in-lbs	4212.000 in-lbs
Distance from NA to section of interest	0.665 in	0.665 in	0.665 in
Max Stress	689.395 psi	689.395 psi	373.423 psi
Stress Ratio	0.26	0.26	[illegible]

Table B-3b. Detail Stress Transfer Functions for the Cape-Class

Transverse Details

	Detail #49	Detail #28F	Detail #36
Trans. Frame Length	36 in	36 in	36 in
Trans. Flange Width	3.000 in	3.000 in	3.000 in
Trans Flange Thickness	0.250 in	0.250 in	0.250 in
Trans. Web Height	9.000 in	9.000 in	9.000 in
Trans. Web Thickness	0.188 in	0.188 in	0.188 in
Trans. Frame Area	2.438 in^2	2.438 in^2	2.438 in^2
Trans. Frame NA height	5.923 in	5.923 in	5.923 in
Inertia of Trans. Frame	22.501 in^4	22.501 in^4	22.501 in^4
Effective Breadth	6.924 in	6.924 in	6.924 in
Combined Section NA	3.792 in	3.792 in	3.792 in
Combined Section INA	53.781 in^4	53.781 in^4	53.781 in^4
Pressure Loading	1 psi	1 psi	1 psi
Load per in	72.000 lb/in	72.000 lb/in	72.000 lb/in
Shear Force at Section	432 lbs	N/A	N/A
Avg. Web Shear Stress	256 psi	N/A	N/A
Max Moment on Section	N/A	3888.000 in-lbs	3888.000 in-lbs
Distance from NA to section of interest	N/A	0.208 in	3.792 in
Max Stress	256.000 psi	15.072 psi	274.100 psi
Stress Ratio	0.13	0.01	0.14

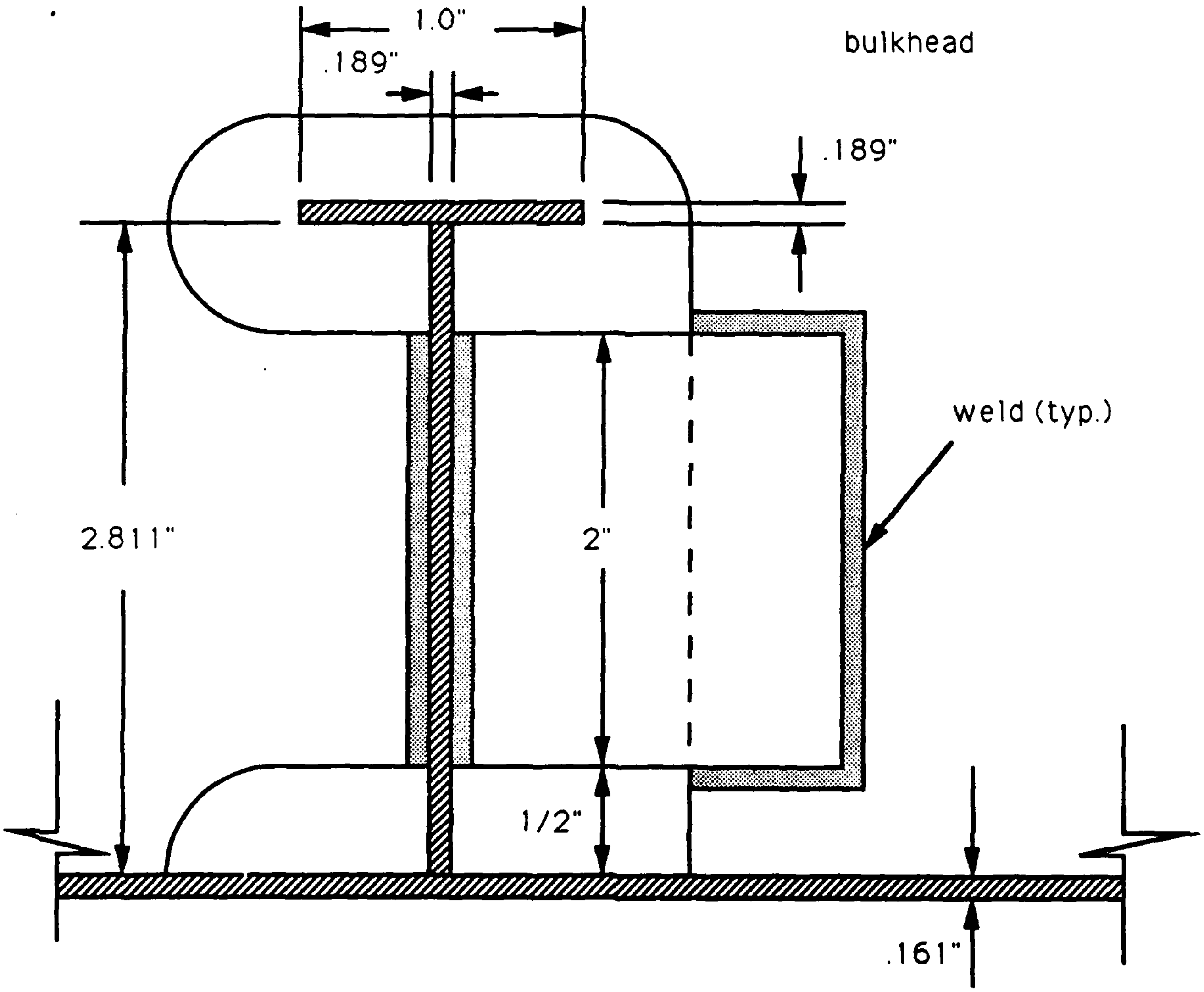

Figure B-1. Fatigue Detail #25 for the Island-Class

APPENDIX C.
STRUCTURAL LIFE ASSESSMENT PROGRAM, SLA.EXE

C.1 INTRODUCTION

C.1.1 Overview

The provided computer program in the program listing at the end of this appendix and on a floppy disk contains the program file and six data files. The program was written in Microsoft QuickBASIC® 4.0 and uses extensive function and sub-routine calls. The majority of the program is devoted to the display of results and user interaction, while the computational part is relatively much less. The user is guided through the program by a series of prompts in which pressing the yellow highlighted letter executes that choice. The program may be stopped at any time (except when Scroll Lock is on) by pressing Control Q.

C.1.2 Warning

Commercial software is put out to certain corporate clients for extensive trial use and debugging before being offered for sale. It would be a very large task to trap all unreasonable input and to test every conceivable combination of input parameters in this program, due in part to the nature of its task. Care must be given to the variation of parameters and the results compared to a reference case in order to be sure of sensible output.

C.1.3 Limitations

The program was written on an IBM AT clone with an EGA color monitor and math co-processor. The machine has a 10 megahertz clock speed and the program takes about thirty five to forty minutes to run at 2000 and 500 simulation cycles for plastic plate deformation and fatigue, respectively. It is not expected to run on a machine that has less than 640 by 350 screen resolution. The program has been tested on the IBM PS50 and PS70. The higher clock speed of the 386 machine runs the program in about 20 to 25 minutes.

The results are calculated for every second year up to thirty. Greater increments could have been chosen in order to reduce the running time, but since this would have meant broader interpolation and some accuracy may have been lost, a two-year increment was selected.

The program and the data files must be in the same directory.

C.1.4 Negative Trapping

For variables with a large COV it is quite possible to generate negative values, which have no meaning for most of the variables used. For example, negative wastage indicates the plating growing over time; negative load cycles does not convey a meaningful value in the program. In some cases negative values cause the probability of failure in a cycle to

evaluate to zero or one; in other cases they cause math errors such as division by zero, or negative number raised to a fractional power. The program tests for these negatives, and when encountered, picks another random number. Eliminating the entire cycle results in reducing the number of cycles of simulation while having the same effect on the distribution as picking a new random number. This has the effect of truncating the distribution without reducing the population. There is another possible alternative which is to reduce all negative numbers to zero. This would skew the distribution with a large spike at zero.

C.1.5 Random Numbers

Micro computers differ in the way that they generate random numbers. In other words, a successive list of numbers from the same seed will always be the same on the same machine, although the list may be different on a different machine type or model. Additionally, QuickBASIC has been found to have some quirks with respect to seeding or re-seeding the random number strings. The program allows for fixed or variable (clock based) seeding, but all analysis to date were performed by starting the program from scratch each time with the fixed seed. For the number of simulation cycles used for the reference cases, the sensitivity of the results to the seed is relatively small.

C.2 DATA FILES AND INPUT

C.2.1 Data Files

Data for the parameters of the reference cases are stored in two files. The ship-specific data, which are mostly displayed on the left side of the input screen, as shown in Figure C-1, are stored as a vector in files called CG095.DAT, CG110.DAT AND CG120.DAT, for the Cape, Island, and Heritage-Class patrol boats, respectively. For example, the boat specific data file CG110.DAT for the Island-Class patrol boat is shown in Table C-1. The remaining part of the input screen contains the plate deformation related parameters, the fatigue detail information and the definition of the case (boat speed/sea state combination) of the operation profile. This information is listed in a concise format. These case specific data are stored in file CG000.DAT, and are displayed on the input screen. An example case specific data file CG000.DAT is shown in Table C-2.

The two remaining data files CG00F.HIS and CG00F.PAR contain the fatigue histogram and the fatigue detail parameters, respectively. The fatigue parameters are listed by line in the order of: name; slope of S-N line, m; intercept, Log C; coefficient of variation of S-N line; and Weibull shape parameter, k. Parameter k was determined for each of the thirteen details considered in this study, by an iterative routine outside of the program.

C.2.2 Input

Input is made in the Input Screen shown in Figure C-1, by editing the displayed parameters of the boats' reference cases. Care has been taken to

```
Specific Data For:                      Case Data:

      ISLAND CLASS  110'
                                         Ship Speed (H,M,L): M  24  kts
Displacement: 165.12  long tons          Wave Height (H,M,L): H  10  ft
LWL: 104.0  ft  Draft:  6.48  ft         Percent Use: 1.00  ( 0.50) %  N
Chine Length:104.0  Beam 19.5            Max/Design Ratio: 0.5943

Deadrise Angle: 12.0  degrees            Annual Use:  2,167  ( 0.40) hrs  N
Max Mean Pressure: 13.37  (calc'd)       Wastage: 1.0  ( 0.25) mil/yr  N
Criterion: 6   plates of 28              Deformation Criterion w/t: 3.00

w: 11.75  ( 0.05) in  N                  Random Number F/V: F
l: 23.50  ( 0.05) in  N                  Yielding Simulation Cycles:  2,000
t: 0.161  ( 0.01) in  N
                                         Fatigue:
Mod-E: 29,774  ( 0.04) ksi  N            Head Seas Use:  19.7  ( 0.50) %  N
Yield 47.8  ( 0.130) ksi  N              Load Cycles:  1,402 ( 0.30) /hr  N
Swp: 2.667  ( 0.20) psi  N               Fatigue Simulation Cycles:    500
                                                        Run Number:  5,239
                  <Space> when finished with editing.
```

Figure C-1. Input Screen

Table C-1. Ship Specific Data File CG110.DAT

Global Variable	Name	File listing
ST$(1)		ISLAND CLASS 110'
v(1)	Displacement	165.12
v(2)	Waterline Length	104
v(3)	Draft	6.48
v(4)	Max. Chine Length	104
v(5)	Max. Chine Beam	19.5
v(6)	Deadrise Angle	12
v(7)	Plate No. Criterion	6
v(8)	Plates in Region	28
v(9)	Mean Max. Pressure	(Calculated)
v(10)	Max/Design Ratio	.594317
v(11)	Mean Plate Width	11.75
v(12)	COV Plate Width	.05
ST$(2)	Distribution type	N
v(13)	Mean Plate Length	23.5
v(14)	COV Plate Length	.05
ST$(3)	Distribution type	N
v(15)	Mean Thickness	.161
v(16)	COV Thickness	.01
ST$(4)	Distribution type	N
v(17)	Mean Modulus of Elasticity	29774
v(18)	COV Modulus Elasticity	.038
ST$(5)	Distribution type	N
v(19)	Mean Yield Strength	47.8
v(20)	COV Yield Strength	.13
ST$(6)	Distribution type	N
v(21)	Mean Static Press.	2.667
v(22)	COV Static Press.	.21
ST$(7)	Distribution type	N
v(27)	Mean Annual use	2167
nBasFtypes	No. of Fatigue Types	4
nFdet(i), Ftype$(i), Fsr(i)	Qty, Name, Stress Ratio	76, 36, .21 12, 25, .1 4, 10A, .03 14, 4, .05
OpCell(i,j), j = 1 to 4	Speed, Wave Height, Max./Design Ratio, Percent Use	12, 3, .129606, 4 24, 3, .125251, 1.7 29, 3, .126342, 1 12, 8, .382097, 4.7 24, 8, .331695, 1.3 29, 7, .147135, .7 12, 10, .443454, 5.3 24, 10, .594317, 1

Table C-2. Case Specific Data File CG000.DAT

Global Variable	Name	File listing
v(25)	Mean Percent Use	1
v(26)	COV Percent Use	.5
ST$(8)	Distribution type	N
v(27)	Mean Annual Use	2167
v(28)	COV Annual Use	.4
ST$(9)	Distribution type	N
v(29)	Mean Wastage	1
v(30)	COV Wastage	.25
ST$(10)	Distribution type	N
v(31)	Mean Percent Use in Head Seas	19.7
v(32)	COV Percent Use in Head Seas	.5
ST$(11)	Distribution type	N
v(33)	Mean No. Loading Cycles	1402
v(34)	COV No. Loading Cycles	.3
ST$(11)	Distribution type	N
v(35)	Deformation Ratio	3
v(36)	No. Yielding Simulation Cycles	2000
ST$(12)	Random Number Seed	F
v(37)	No. Fatigue Simulation Cycles	500
v(38)	Run Number	5237
ST$(14)	Ship Speed H, M, or L	M
ST$(15)	Wave Height H, M, or L	H

make the program "user friendly." Letters highlighted in yellow determine the choices at each screen, and pressing the space bar allows the program to proceed through the next step. One letter of each input parameter is displayed in yellow during the edit mode. Pressing one of those letters prompts for a new value and immediately displays it in the appropriate field. To edit the COV or distribution type, the user enters lower case v or x, respectively, and the program will wait for him/her to identify the variable. The variables on the right side of the screen (except wastage) are calculated with a normal probability distribution regardless of what is displayed.

Basic© and or QuickBASIC© have limitations that dictate how certain tasks are performed. For example, allowing the user to move around the different data fields using the cursor keys, which would have been nice, would have required more programming effort than was justified in the non-computational part of the program. It was also impractical to program the escape key to undo certain keystrokes.

C.3 PROGRAM ORGANIZATION

QuickBASIC© 4.0 allows sub-programs and function procedures that are mini programs called by the main program and which may have their own local variables like Fortran sub-routines. It also allows the old type of subroutine where all variables are global and the program flow is transferred to the subroutine and then either returned or diverted depending on whether the sub-routine was called with GOSUB or GOTO. A list of all three types follows. The identification of the variables is in the subroutines themselves, and is given in local variable names.

C.3.1 SUB B (NRow, NCol, Strin$)

This is used extensively in expressions of the type B 10,23," ". It saves using the LOCATE and PRINT commands for every statement output to the screen.

C.3.2 SUB C (NRow, NCol, NSpace)

The brackets that enclose the COV in the display are printed by this sub-program.

C.3.3 SUB D (NRow, NCol, Value, Format$)

Sub D performs the same function as Sub B for non-integer variables.

C.3.4 SUB CLM ()

CLear Message has no arguments, hence the empty parentheses, but simply erases the prompt message on line 23 of the display.

C.3.5 SUB DLINE (Row!, Col!, hv$, leng!, Ncolr)

The graph displays use Dline to draw either vertical or horizontal lines.

C.3.6 SUB SeaSpeed (NV, s$, w$, OpCell(), vel, Wht, Ratio, PcUse, Uhs)

The designation for sea state (High, Medium, or Low) and boat speed (High, Medium, or Low) are converted into specific numerical values that depend on boat type.

C.3.7 SUB DesPressure (vel, Dell, Bc, beta, Wht, Lp, Dr, w, l, Lwl, Ratio, Pd)

The dynamic design pressure is calculated as in Section 5.1 of the report, and converted by the applicable ratio to a mean maximum pressure. The ratio relates the calculated dynamic design pressure to the mean of the maximum pressures measured in each speed/sea state combination (case) for the Island-Class patrol boat.

C.3.8 SUB ExtremePressure (P, Pc, Ti, Au, U, nYr, EP, EPsd, An, Un)

This sub-program calculates the mean and coefficient of variation of the extreme pressure distribution from the maximum pressure parent distribution. The parameters of the extreme value distribution are returned to be used in the main program when the value GofX (the pressure strength of the plates to bending, minus the static pressure) is evaluated at the CDF of the extreme value distribution.

C.3.9 SUB Fatigue (v(), Cyr(), nFtypes, nOrd(), Fsr(), Fpar(), nFdet(), Pff(), COVPff(), Hfd())

A vector containing all values generated for the number of cycles per year (Cyr) is passed to Fatigue, which evaluates the probability of failure of each detail in every second year at each cycle, and returns the mean value and coefficient of variation for each detail at every second year.

C.3.10 FUNCTION PhiInv (R)

The inverse of the standard normal distribution is calculated for a random number R, where R is between zero and one.

C.3.11 FUNCTION GofX (w, l, t, Em, SigY, Swp, Wstg, wp)

Pronounced g(x), this function returns the value at which the cumulative distribution function (CDF) of the extreme pressure will be evaluated in each cycle. It is the pressure strength of the plate minus the static (still water) pressure. It is evaluated four times in each cycle because antithetic variates VRT (variation reduction technique) produces two values of thickness and two values of wastage giving a total of four thickness values at which the strength must be evaluated.

C.3.12 SUB Binomial (ZONE, AREA, PFP, PfB)

The probability of failure of n_p plates out of N_p plates in the critical region, given the probability of failure of a plate, is given by the PMF (probability mass function) of the binomial distribution. This probability is evaluated in this sub-program.

C.3.13 FUNCTION FACT (I)

The factorial function for the binomial distribution is evaluated by this function.

C.3.14 SUB GraphY (Pfy(), v(), ST$(), tt, F22$)

This sub-program draws the visual output screen of the yielding part of the program.

C.3.15 SUB GraphF (nFtypes, Ftype$(), Pff(), Hfd(), v(), ST$(), HN)

This sub-program draws the visual output screen of the fatigue part of the program.

C.3.16 SUB GraphSL (PfSLll(), PfSLul(), v(), ST$(), tt, F22$)

The graphs of yielding and fatigue are combined into an upper and lower limits and the user is prompted to save the results to a file.

C.3.17 Subroutines

The subroutines called here "of the old type", perform tasks related to data input and or display, and their names convey their roles: Title; DataInput; PrintVarname; PrintValues; EditVarble; EDITT; FatigueScreen; ZeroMessage; FileOut; and ERRoutine.

C.4 MAIN PROGRAM

The main program contains the bulk of the computation and calls specific subroutines in a way that is designed to be easy to follow. In each cycle, it first generates two values for each of the first six parameters (width, length, thickness, E, Fy, and still water pressure), it then generates two values for wastage every two years from 2 to 30 years. The only subroutine called is PhiInv(R). In the same loop of years, it calls the ExtremePressure and GofX subroutines to evaluate a probability of failure for every second year for that cycle and adds them each to the sum of the probabilities of failure in all preceding cycles.

After looping through all cycles, the mean and coefficient of variation (which is the probability of failure of any one plate) are determined for every second year and displayed. Finally, the Binomial subroutine is called and then the data are interpolated linearly for odd numbered years. The results are displayed graphically by GraphY.

In the fatigue part of the program, random variables are generated for annual use, percent use in head seas, and loading cycles per year, combined into a value of loading cycles per year and stored in a vector. The vector is then transferred to the Fatigue subroutine as explained above, then the returned probability of failure is displayed by GraphF.

C.5 OUTPUT

C.5.1 Screen Output

The results are displayed graphically in three screens, yielding, fatigue, and combined upper and lower limits for the structural system. In general, the upper and lower limits are displayed as one line unless the results are of about the same order of magnitude. In each screen, there is a graph which is scaled to show the probability of failure at thirty years near the top of the graph. The scaling factor is displayed in the form "Pf x 1D+0#". This means that for example .2 on the ordinate would be read as .2 times 10 to the minus #, or 2 times 10 to the minus (# - 1).

C.5.2 Output to Files

When the "Save Output" prompt at the final screen is selected, all input data, the probability of failure at each year in yielding, fatigue and upper and lower limits of the structural system's probabilities of failure, and the run number are saved in a file in the current DOS directory with the name CG####.OUT, where #### is the run number. Another file named CG####.123 contains the numerical results of yielding and fatigue at each year in a form that can be read into Lotus 123. The procedure is to use the / File Import Numbers command and then combine the pairs of columns that contain the number and its exponential part. This can also be used on the CG####.OUT file, but there is more extraneous information. These output files can be printed using the DOS "print CG####.out" command.

C.6 LISTING OF COMPUTER PROGRAM SLA.EXE

```
'MOD14.BAS   7/4/89  Compiled as SLA.EXE
'Reliability-based Structural Life Assessment
'Ayyub, White, and Bell-Wright, University of Maryland, College Park
'Civil Engineering Department
DEFINT H-K, N
DEFDBL A-F, L-M, O-Z
DECLARE SUB B (NRow, NCol, Strin$)
DECLARE SUB C (NRow, NCol, NSpace)
DECLARE SUB D (NRow, NCol, Value, Format$)
DECLARE SUB CLM ()
DECLARE SUB DLINE (Row!, Col!, hv$, leng!, Ncolr)
DECLARE SUB SeaSpeed (NV, s$, w$, OpCell(), vel, Wht, Ratio, PcUse, Uhs)
DECLARE SUB DesPressure (vel, Dell, Bc, beta, Wht, Lp, Dr, w, 1, Lwl, Ratio,
Pd)
DECLARE SUB ExtremePressure (P, Pc, Ti, Au, U, nYr, EP, EPsd, an, Un)
DECLARE SUB Fatigue (v(), Cyr(), nFtypes, nOrd(), Fsr(), Fpar(), nFdet(),
Pff(), COVPff(), Hfd())
DECLARE FUNCTION PhiInv (R)
DECLARE FUNCTION GofX (w, 1, t, Em, SigY, Swp, Wstg, wp)
DECLARE SUB Binomial (ZONE, AREA, PFP, PfB)
DECLARE FUNCTION FACT (I)
DECLARE SUB GraphY (Pfy(), v(), ST$(), tt, F22$)
DECLARE SUB GraphF (nFtypes, Ftype$(), Pff(), Hfd(), v(), ST$(), HN)
DECLARE SUB GraphSL (PfSLl1(), PfSLul(), v(), ST$(), tt, F22$)
'
DIM Var(7, 2), Pfy(30), Vart(30, 4), PfSum(30), PfSumSq(30)
DIM MaxErr(2, 2), v(40), f(40), fT$(15), ST$(15), Epm(30), Eps(30), ttcum(30)
DIM nFdet(17), Pff(30, 17), Hfd(30), Fpar(17, 5), PfSL11(30), PfSLul(30)
DIM Ftype(17) AS STRING, nOrd(17) AS INTEGER, OpCell(8, 4)
DIM Cyr(2500), COVPff(30, 17), Au(2), Up(2), Rv(3), Fdet$(17), Fsr(17)
DIM rFlag, r2Flag, yFlag, fFlag, f2Flag, f3Flag AS INTEGER
'
ON ERROR GOTO ERRoutine
'Trap <Ctl> Q with Num Lock, Caps Lock or both
KEY 15, CHR$(4) + CHR$(16): KEY 16, CHR$(36) + CHR$(16)
KEY 17, CHR$(68) + CHR$(16): KEY 18, CHR$(100) + CHR$(16)
ON KEY(15) GOSUB Break: ON KEY(16) GOSUB Break
ON KEY(17) GOSUB Break: ON KEY(18) GOSUB Break
KEY(15) ON: KEY(16) ON: KEY(17) ON: KEY(18) ON
'
F1$ = "#": F11$ = "##.#": F12$ = "##.##": F13$ = "##.###" 'Name print formats
F14$ = "##.####": F2$ = "##": F21$ = "###.#": F22$ = "###.##"
F23$ = "###.###": F3$ = "###": F31$ = "####.#": F32$ = "####.##"
F5$ = "######,": FE$ = "#.####^^^^"
'
OPEN "I", 1, "CG000.DAT"                                 'Read data file
FOR K = 25 TO 37 STEP 2
  INPUT #1, f(K): v(K) = f(K)
  INPUT #1, f(K + 1): v(K + 1) = f(K + 1)
  INPUT #1, fT$((K - 9) / 2): ST$((K - 9) / 2) = fT$((K - 9) / 2)
NEXT K
INPUT #1, fT$(15): ST$(15) = fT$(15)
```

```
CLOSE #1
f(38) = f(38) + 1                                        'Increment run number
'
GOSUB Title
     ' ____
Start:                                               'Initialize routing flags
rFlag = 0: r2Flag = 0: yFlag = 0: fFlag = 0: f2Flag = 0: f3Flag = 0
GOSUB DataInput
     ' ________
MAIN:
SCREEN 9
v(17) = v(17) * 1000!                                             'Adjust units
v(19) = v(19) * 1000!
v(29) = v(29) / 1000!
tt = TIMER
Pi = 3.1415926536#
'
SELECT CASE ST$(13)                                         'Random number seed
  CASE "F"
    RANDOMIZE 10567
  CASE "V"
    RANDOMIZE TIMER
END SELECT
'
FOR I = 1 TO 30
  PfSum(I) = 0
  PfSumSq(I) = 0
NEXT I
'
Ti = 30!                               'Interval of measured pressure giving max
Pc = .1                                                   'COV of max pressures
IF ST$(14) = "M" AND ST$(15) = "H" THEN
  Ti = 10                                'Interval and COV only differ in cell 8
  Pc = 1!
END IF
'
N1 = 1                                      'Draws squares indicating progress
IF v(36) >= 200 THEN                        '
  N1 = 64                                   '
ELSE                                        '
  COLOR 15, 0: B 9, 35, "Stand By..."       '
END IF                                      '
N2 = v(36) / N1                             '
FOR N = 1 TO N1                             '
  NX = (N - 1) * 10                         '
  LINE (NX, 112)-(NX + 5, 116), 15, BF      '
  FOR NN = 1 TO N2                                   'Generate random variables
    FOR I = 11 TO 24 STEP 2                          'w, 1, t, E, SigmaY, Swp.
      HH = (I - 7) / 2
      H = HH - 1
      R = RND
      Ph = PhiInv(R)
          '________                                     'Sub-program calls thus
      IF I <> 23 THEN
```

```
          s = v(I) * v(I + 1)
          SELECT CASE ST$(HH)
            CASE "N"                                          'Normal
              Var(H, 1) = v(I) + Ph * s
              Var(H, 2) = v(I) - Ph * s
            CASE "L"                                          'Log Normal
              Zet2 = SQR(LOG(1 + v(I + 1) ^ 2))
              Lamb = LOG(v(I)) - .5 * Zet2
              Var(H, 1) = EXP(Lamb + Ph * SQR(Zet2))
              Var(H, 2) = EXP(Lamb - Ph * SQR(Zet2))
          END SELECT
        ELSE

          FOR J = 2 TO 30 STEP 2          'Generate wastage at every 2 years.
            MW = .926733 * v(29) * J ^ .8082008 'Mean Wastage in year J (4-17)
            COVW = .41305 * v(30) ^ .2864022 * J ^ .299329             '(4-18)
            s = MW * COVW                                ' Standard deviation
NegTrap3:
            Vart(J, 1) = (MW + Ph * s)
            Vart(J, 2) = (MW - Ph * s)
            FOR K = 1 TO 2               'Eliminate negative values of wastage
              IF Vart(J, K) < 0 THEN
                Ph = PhiInv(RND)
                '______________
                GOTO NegTrap3
              END IF
            NEXT K
          NEXT J
        END IF
      NEXT I
'
      FOR I = 2 TO 30 STEP 2
NegTrap1:
        Ph = PhiInv(RND)                                 'Generate Annual use
            '______________
        Au(1) = v(27) + Ph * v(27) * v(28)
        Au(2) = v(27) - Ph * v(27) * v(28)
        FOR K = 1 TO 2                              'Eliminate negative values
          IF Au(K) < 0 THEN
            GOTO NegTrap1
          END IF
        NEXT K
NegTrap2:
        Ph = PhiInv(RND)                                'Generate Percent use
            '______________
        Up(1) = v(25) + Ph * v(25) * v(26)
        Up(2) = v(25) - Ph * v(25) * v(26)
        FOR K = 1 TO 2                              'Eliminate negative values
          IF Up(K) < 0 THEN
            GOTO NegTrap2
          END IF
        NEXT K
        Sum = 0
        FOR K = 1 TO 2                        'Get 2 values of extreme pressure
```

```
          ExtremePressure v(9), Pc, Ti, Au(K), Up(K), I, Epm(K), Eps(K), Alp,U
         '
          FOR J = 1 TO 2     'Get 4 values of Resistance minus static pressure
            DUM3 = GofX(Var(1, K), Var(2, K), Var(3, K), Var(4, K), Var(5, K),
                  Var(6, K), Vart(I, J), v(35))
                      'Get 4 Prob. failure in cycle (N * NN) at year I (4-9)
            Pf = 1 - EXP(-EXP(-Alp / v(9) / Pc * (DUM3 - v(9) * (1 + Pc *U))))
            Sum = Sum + Pf / 4!
          NEXT J
        NEXT K
        PfSum(I) = PfSum(I) + Sum          'Sum the Pf for every second year
        PfSumSq(I) = PfSumSq(I) + Sum ^ 2
      NEXT I
    NEXT NN                                'Draw red squares
    LINE (NX, 112)-(NX + 5, 116), 4, BF     '
NEXT N
'
ReviewPf:                                  'A marker for reviewing screens
CLS
IF PfSum(30) = 0 THEN
  GOSUB ZeroMessage
  GOTO Fatigue
END IF
'
SCREEN 0: COLOR 15, 1
B 2, 29, "  Pf of Any One Plate  "
B 2, 65, "          ": D 2, 65, v(38), F5$
FOR I = 2 TO 30 STEP 2
  MeanPF# = PfSum(I) / v(36)
  VarPF = ABS(PfSumSq(I) - v(36) * MeanPF# ^ 2)/(v(36) - 1)/ v(36)
  COVPF = SQR(VarPF) / MeanPF#
  B 4, 14, "  Year      Mean        COV        Variance  "
  LOCATE (I + 8) / 2, 11
  PRINT USING "      ###      ##.####^^^^   ##.####^^^^   ##.####^^^^    ";
I, MeanPF#, COVPF, VarPF
  '
  Binomial v(7), v(8), MeanPF#, Pfy(I)     'Pf of (e.g.) 6 plates out of 28
  '
NEXT I
'
IF rFlag = 0 THEN BEEP: BEEP
B 23, 4, "            Restart      Data screen      Exit     <Space> to
continue "
COLOR 14, 1: B 23, 17, "R": B 23, 31, "D": B 23, 50, "E"
B 23, 60, "<": B 23, 66, ">"
COLOR 15, 1
PROMPT19:
AA$ = INKEY$: IF AA$ = "" THEN : GOTO PROMPT19:    ELSE GOSUB MENU19
'
SCREEN 9
Pfy(0) = 0
FOR I = 1 TO 29 STEP 2              'Interpolate linearly for odd year values
  Pfy(I) = (Pfy(I - 1) + Pfy(I + 1)) / 2!
NEXT I
```

```
'
yFlag = 0
v(19) = v(19) / 1000!                                           'Adjust units
v(17) = v(17) / 1000!
v(29) = v(29) * 1000!
'
Review:
GraphY Pfy(), v(), ST$(), tt, F22$                              'Draw yielding graph
'
B 23, 17, "Restart    Pf      Data screen     Exit     <Space> to continue"
COLOR 14, 1: B 23, 17, "R": B 23, 28, "P": B 23, 36, "D": B 23, 52, "E"
B 23, 60, "<": B 23, 66, ">"
COLOR 15, 1
PROMPT9:
AA$ = INKEY$: IF AA$ = "" THEN : GOTO PROMPT9:      ELSE GOSUB MENU9
'
'       ********** END YIELDING, BEGIN FATIGUE ***********
Fatigue:
IF fFlag = 0 THEN
  OPEN "I", 1, "CGOOF.PAR"   'Read the parameters of standard fatigue details
  FOR K = 1 TO 13
    INPUT #1, Fdet$(K), Fpar(K, 1), Fpar(K, 2), Fpar(K, 3), Fpar(K, 4)
  NEXT K
  CLOSE #1
  fFlag = 1
END IF
'
ReviewF:
GOSUB FatigueScreen
IF f2Flag = 1 THEN GOTO ReviewF2
'
' Generate a distribution of values for number of loading cycles in a year
SCREEN 9
N1 = 1: NI = 0                                'Draw yellow squares
IF v(37) >= 200 THEN                          '
  N1 = 64                                     '
ELSE                                          '
  COLOR 14, 0: B 9, 35, "Stand By..."         '
END IF                                        '
N2 = v(37) / N1                               '
FOR N = 1 TO N1                               '
  NX = (N - 1) * 10                           '
  LINE (NX, 112)-(NX + 5, 116), 15, BF        '
  FOR NN = 1 TO N2                            '
    NI = NI + 1
NegTrap4:                                                'Generate Annual use
    Ua = v(27) + PhiInv(RND) * v(27) * v(28)
                  '
    IF Ua < 0 THEN GOTO NegTrap4
NegTrap5:                                        'Generate % use in head seas
    Uph = v(31) + PhiInv(RND) * v(31) * v(32)
                  '
    IF Uph < 0 THEN GOTO NegTrap5
NegTrap6:
```

```
      Cyc = v(33) + PhiInv(RND) * v(33) * v(34)        'Generate loading cycles
                          '
      IF Cyc < 0 THEN GOTO NegTrap6
      '
      Cyr(NI) = Ua * Uph * Cyc                          'The vector of all values
    NEXT NN                                             'of loading cycles/year
    LINE (NX, 112)-(NX + 5, 116), 14, BF
NEXT N
'
Fatigue v(), Cyr(), nFtypes, nOrd(),Fpar(),Fsr(),nFdet(),Pff(),COVPff(),Hfd()
'
FOR J = 1 TO nFtypes                ' Interpolate linearly for odd year values
  FOR I = 1 TO 29 STEP 2
    Pff(I, J) = (Pff(I - 1, J) + Pff(I + 1, J)) / 2!
  NEXT I
NEXT J
'
f2Flag = 1
ReviewF2:                                                      'Graph Fatigue
GraphF nFtypes, Ftype$(), Pff(), Hfd(), v(), ST$(), HN
'
B 23, 14, "Restart     Yielding     Fatigue params     <Space> to continue"
COLOR 14, 1: B 23, 14, "R": B 23, 27, "Y": B 23, 41, "F"
B 23, 60, "<": B 23, 66, ">"
COLOR 15, 1
Prompt15:
AA$ = INKEY$: IF AA$ = "" THEN : GOTO Prompt15:     ELSE GOSUB MENU15
'
'        ******************** END FATIGUE *****************
                 'Find upper and lower limits of combined Yielding and Fatigue
FOR I = 1 TO 30
  IF Pfy(I) > Pff(I, HN) THEN       'Pf = Probability of Failure
    PfSLll(I) = Pfy(I)              'y = yielding
  ELSE                              'f = fatigue
    PfSLll(I) = Pff(I, HN)          'll = lower limit
  END IF                            'ul = upper limit
  PfSLul(I) = 1 - (1 - Pfy(I)) * (1 - Pff(I, HN))                      '(6-1)
NEXT I
'
ReviewSL:                                        'Draw graph of struct. life
GraphSL PfSLll(), PfSLul(), v(), ST$(), tt, F22$
'
B 23, 11, "Save output   Restart   Yielding   Fatigue   <Space> to
continue"
COLOR 14, 1: B 23, 11, "S": B 23, 26, "R": B 23, 37, "Y": B 23, 49, "F"
B 23, 60, "<": B 23, 66, ">"
COLOR 15, 1
Prompt16:
AA$ = INKEY$: IF AA$ = "" THEN : GOTO Prompt16:     ELSE GOSUB MENU16
'
OPEN "O", 1, "CG000.DAT"
FOR K = 25 TO 37 STEP 2
  PRINT #1, f(K)
  PRINT #1, f(K + 1)
```

```
  PRINT #1, fT$((K - 9) / 2)
NEXT K
PRINT #1, fT$(15)
CLOSE #1
'
END
'************************* END OF MAIN PROGRAM ****************************
MENU19:
'-------
rFlag = 0
SELECT CASE AA$
  CASE "R", "r"
    CLM
    rFlag = 1: GOTO Start
  CASE "D", "d"
    rFlag = 1: r2Flag = 0
    v(19) = v(19) / 1000!
    v(17) = v(17) / 1000!
    v(29) = v(29) * 1000!
    GOSUB DataInput
    v(19) = v(19) * 1000!
    v(17) = v(17) * 1000!
    v(29) = v(29) / 1000!
    B 23, 42, "<Space> to return to Pf of a Plate"
    COLOR 14, 1: B 23, 42, "<": B 23, 48, ">": COLOR 15, 1
PROMPT20:
    AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT20
    SELECT CASE AA$
      CASE CHR$(32): SCREEN 9: GOTO ReviewPf
      CASE ELSE: GOTO PROMPT20
    END SELECT
  CASE "E", "e": CLS : SCREEN 0: END
  CASE CHR$(32)
  CASE ELSE: GOTO PROMPT19
END SELECT
RETURN
'--------------------------------------------------------------------------
MENU9:
'------
rFlag = 0
SELECT CASE AA$
  CASE "R", "r"
    CLM
    rFlag = 1: GOTO Start
  CASE "P", "p"
    rFlag = 1
    v(19) = v(19) * 1000!
    v(17) = v(17) * 1000!
    v(29) = v(29) / 1000!
    GOTO ReviewPf
  CASE "D", "d"
    rFlag = 1: r2Flag = 0
    GOSUB DataInput
    B 23, 42, "<Space> to return to graph screen"
```

```
    COLOR 14, 1: B 23, 42, "<": B 23, 48, ">": COLOR 15, 1
PROMPT10:
    AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT10
    SELECT CASE AA$
      CASE CHR$(32): rFlag = 1: GOTO Review
      CASE ELSE: GOTO PROMPT10
    END SELECT
  CASE "E", "e": SCREEN 0: END
  CASE CHR$(32)
  CASE ELSE: GOTO PROMPT9
END SELECT
RETURN
'-----------------------------------------------------------------
MENU15:
'------
rFlag = 0
SELECT CASE AA$
  CASE "R", "r"
    CLM
    rFlag = 1: GOTO Start
  CASE "Y", "y"
    IF yFlag = 1 THEN
      rFlag = 1: r2Flag = 1: GOTO Start
    ELSE
      CLS
      rFlag = 1: GOTO Review
    END IF
  CASE "F", "f"
    CLS
    f3Flag = 1
    GOTO ReviewF
  CASE CHR$(32)
  CASE ELSE: GOTO Prompt15
END SELECT
RETURN
'-----------------------------------------------------------------
MENU16:
'------
rFlag = 0
SELECT CASE AA$
  CASE "S", "s"
    GOSUB FileOut
    GOTO Prompt16
  CASE "R", "r"
    CLM
    rFlag = 1: GOTO Start
  CASE "Y", "y"
    IF yFlag = 1 THEN
    rFlag = 1: r2Flag = 1: GOTO Start
  ELSE
    CLS
    rFlag = 1: GOTO Review
  END IF
  CASE "F", "f"
```

```
    CLS
    GOTO ReviewF2
  CASE CHR$(32)
  CASE ELSE: GOTO Prompt16
END SELECT
RETURN
'----------------------------------------------------------------------------
Title:
'-----
SCREEN 0: CLS
Ins = 22
COLOR 15, 1: LOCATE 4, Ins
PRINT "                                    ": LOCATE 5, Ins
PRINT "         Reliability-Based          ": LOCATE 6, Ins
PRINT "     Structural Life Assessment     ": LOCATE 7, Ins
PRINT "                                    ": LOCATE 8, Ins
PRINT "                                    ": LOCATE 8, Ins + 14: COLOR 14, 4
PRINT " S.L.A. ": LOCATE 9, Ins: COLOR 15, 1
PRINT "                                    ": LOCATE 10, Ins
PRINT "                 by                 ": LOCATE 11, Ins
PRINT "                                    ": LOCATE 12, Ins
PRINT "      Bilal M. Ayyub, Ph.D., PE     ": LOCATE 13, Ins
PRINT "       Gregory J. White, Ph.D.      ": LOCATE 14, Ins
PRINT "        Thomas F. Bell-Wright       ": LOCATE 15, Ins
PRINT "                                    ": LOCATE 16, Ins
PRINT "       College Park, Maryland       ": LOCATE 17, Ins
PRINT "           (301) 454-2211           ": LOCATE 18, Ins
PRINT "                                    ": LOCATE 19, Ins
PRINT "             Version 2.0            ": LOCATE 20, Ins
PRINT "           Copyright 1989           ": LOCATE 21, Ins
PRINT "                                    "
B 23, 60, " <Space> to continue "
COLOR 14, 1: B 23, 61, "<": B 23, 67, ">": COLOR 15, 1
PROMPT7:
AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT7
SELECT CASE AA$
  CASE CHR$(32): RETURN
  CASE ELSE: GOTO PROMPT7
END SELECT
RETURN
'----------------------------------------------------------------------------
DataInput:
'---------
SCREEN 0: COLOR 7, 0: CLS : COLOR 15, 1
IF rFlag = 1 THEN GOTO Restart
COLOR 15, 4: B 1, 1, STRING$(80, 32)
FOR I = 1 TO 23
  B I, 1, "  ": B I, 79, "  "
NEXT I
B 23, 1, STRING$(80, 32): COLOR 14, 4
B 23, 23, "<Ctl> Q  quits program at any time"
COLOR 15, 1
B 7, 25, "                               "
B 8, 25, "  Select ship type for analysis  "
```

```
B 9, 25, "                                  "
B 13, 22, "                                      "
B 14, 22, "   Cape Class  95 foot Patrol Boat    "
B 15, 22, "                                      "
B 16, 22, "  Island Class  110 foot Patrol Boat  "
B 17, 22, "                                      "
B 18, 22, "  Heritage Class 120 foot Patrol Boat "
B 19, 22, "                                      "
COLOR 14, 1
B 14, 25, "C"
B 16, 24, "I"
B 18, 24, "H"
Prompt3:
AA$ = INKEY$: IF AA$ = "" THEN GOTO Prompt3
SELECT CASE AA$
  CASE "C", "c"
   Filename$ = "CG095.DAT"
  CASE "I", "i"
   Filename$ = "CG110.DAT"
  CASE "H", "h"
   Filename$ = "CG120.DAT"
  CASE ELSE
   GOTO Prompt3
END SELECT
'
COLOR 4, 11
OPEN "I", 1, Filename$
INPUT #1, ST$(1)                                          'Read ship-specific file
FOR K = 1 TO 10: INPUT #1, v(K): NEXT K
FOR K = 11 TO 21 STEP 2
  INPUT #1, v(K)
  INPUT #1, v(K + 1)
  INPUT #1, ST$((K - 7) / 2)
NEXT K
INPUT #1, v(27)
INPUT #1, nBasFtypes
FOR K = 1 TO nBasFtypes
  INPUT #1, nFdet(K), Ftype$(K), Fsr(K)
NEXT K
FOR K = 1 TO 8
  INPUT #1, OpCell(K, 1), OpCell(K, 2), OpCell(K, 3), OpCell(K, 4)
NEXT K
CLOSE #1
nFtypes = nBasFtypes
'
Restart:
SCREEN 0: COLOR 7, 1: CLS : COLOR 4, 3
B 2, 3, STRING$(37, 220)
B 2, 42, STRING$(38, 220)
B 22, 3, STRING$(37, 223)
B 22, 42, STRING$(38, 223)
FOR I = 2 TO 22
  B I, 2, CHR$(221)
  B I, 39, CHR$(222)
```

```
  B I, 41, CHR$(221)
  B I, 79, CHR$(222)
NEXT I
COLOR 7, 1
GOSUB PrintVarname
      ''''''''''''
COLOR 15, 1
GOSUB PrintValues
     ' __________
IF rFlag = 0 OR r2Flag = 1 OR AA$ = "R" OR AA$ = "r" THEN
  B 23, 30, "Edit     Previous screen     <Space> to continue"
  COLOR 14, 1
  B 23, 30, "E": B 23, 39, "P": B 23, 59, "<": B 23, 65, ">"
  COLOR 7, 1
prompt:
  AA$ = INKEY$: IF AA$ = "" THEN GOTO prompt
  SELECT CASE AA$
   CASE "E", "e": GOTO EditVarble
   CASE "P", "p": rFlag = 0: GOTO DataInput
   CASE CHR$(32): GOTO FatYldQ
   CASE ELSE: GOTO prompt
  END SELECT
END IF
RETURN
'--------------------------------------------------------------------
PrintVarname:
'____________
COLOR 4, 3: B 2, 11, " Specific Data For: ": COLOR 7, 1
B 6, 4, "Displacement:": B 6, 26, "long tons"
B 7, 4, "LWL:": B 7, 16, "ft": B 7, 20, "Draft:": B 7, 34, "ft"
B 8, 4, "Chine Length:": B 8, 24, "Beam:": B 10, 4, "Deadrise Angle:"
B 10, 26, "degrees": B 11, 4, "Max Mean Pressure:": B 11, 30, "(calc'd)"
B 12, 4, "Criterion:": B 12, 19, "plates of": B 14, 4, "w:"
B 14, 22, "in": B 15, 4, "l:": B 15, 22, "in": B 16, 4, "t:": B 16, 22, "in"
B 18, 4, "Mod-E:": B 18, 27, "ksi": B 19, 4, "Yield:": B 19, 25, "ksi"
B 20, 4, "Swp:": B 20, 24, "psi"
COLOR 4, 3: B 2, 55, " Case Data: ": COLOR 7, 1
B 5, 44, "Ship Speed (H,M,L):": B 5, 71, "kts": B 6, 44, "Wave Height
(H,M,L):"
B 6, 72, "ft": B 7, 44, "Percent Use:": B 7, 71, "%"
B 8, 44, "Max/Design Ratio:"
B 10, 44, "Annual Use:": B 10, 72, "hrs": B 11, 44, "Wastage:"
B 11, 66, "mil/yr": B 12, 44, "Deformation Criterion w/t:"
B 14, 44, "Random Number F/V:": B 15, 44, "Yielding Simulation Cycles:"
B 17, 44, "Fatigue:": B 18, 44, "Head Seas Use:": B 18, 74, "%"
B 19, 44, "Load Cycles:": B 19, 72, "/hr": B 20, 44, "Fatigue Simulation
Cycles:"
B 21, 60, "Run Number:"
RETURN
'--------------------------------------------------------------------
PrintValues:
'___________
SeaSpeed NV, ST$(14), ST$(15), OpCell(), v(23), v(24), v(10), v(25), v(31)
'__________
```

```
DesPressure v(23),v(1),v(5),v(6),v(24),v(4),v(3),v(11),v(13),v(2),v(10),v(9)
'__________
B 4, 11, ST$(1): D 6, 17, v(1), F32$: D 7, 8, v(2), F31$
D 7, 26, v(3), F22$: D 8, 17, v(4), F21$: D 8, 28, v(5), F21$
D 10, 19, v(6), F21$: D 11, 22, v(9), F22$: D 12, 14, v(7), F2$
D 12, 28, v(8), F3$
D 14, 6, v(11), F22$: C 14, 14, 5: D 14, 15, v(12), F12$: B 14, 26, ST$(2)
D 15, 6, v(13), F22$: C 15, 14, 5: D 15, 15, v(14), F12$: B 15, 26, ST$(3)
D 16, 6, v(15), F13$: C 16, 14, 5: D 16, 15, v(16), F12$: B 16, 26, ST$(4)
D 18, 10, v(17), F5$: C 18, 19, 5: D 18, 20, v(18), F12$: B 18, 32, ST$(5)
D 19, 9, v(19), F21$: C 19, 16, 6: D 19, 17, v(20), F13$: B 19, 30, ST$(6)
D 20, 8, v(21), F13$: C 20, 16, 5: D 20, 17, v(22), F12$: B 20, 29, ST$(7)
B 5, 64, ST$(14): D 5, 67, v(23), F2$
B 6, 65, ST$(15): D 6, 68, v(24), F2$
D 7, 56, v(25), F12$: C 7, 63, 5: D 7, 64, v(26), F12$: B 7, 74, ST$(8)
D 8, 61, v(10), F14$
D 10, 55, v(27), F5$: C 10, 64, 5: D 10, 65, v(28), F12$: B 10, 77, ST$(9)
D 11, 52, v(29), F11$: C 11, 58, 5: D 11, 59, v(30), F12$: B 11, 74, ST$(10)
D 12, 70, v(35), F12$: B 14, 63, ST$(13): D 15, 71, v(36), F5$
D 18, 59, v(31), F21$: C 18, 66, 5: D 18, 67, v(32), F12$: B 18, 77, ST$(11)
D 19, 56, v(33), F5$: C 19, 64, 5: D 19, 65, v(34), F12$: B 19, 77, ST$(12)
D 20, 70, v(37), F5$: D 21, 71, v(38), F5$
RETURN
'--------------------------------------------------------------------
EditVarble:
'__________
COLOR 1, 1: B 23, 1, STRING$(80, 32)
COLOR 14, 1
B 6, 4, "D": B 7, 4, "L": B 7, 21, "r": B 8, 5, "h": B 8, 24, "B"
B 10, 7, "d": B 12, 12, "n": B 12, 26, "o": B 14, 4, "w": B 15, 4, "l"
B 16, 4, "t": B 18, 8, "E": B 19, 4, "Y": B 20, 6, "p": B 5, 44, "S"
B 6, 44, "W": B 7, 44, "P": B 8, 44, "M": B 10, 44, "A": B 11, 45, "a"
B 12, 46, "f": B 14, 44, "R": B 15, 64, "C": B 18, 45, "e"
B 19, 51, "c": B 20, 44, "F"
COLOR 15, 1
B 23, 5, "Hit letter in proper case. 'v', 'x', then letter, for COV, dist'n."
COLOR 14, 1: B 23, 33, "v": B 23, 38, "x": COLOR 15, 1
Prompt4:
NV = 0: NA = 0
AA$ = INKEY$: IF AA$ = "" THEN GOTO Prompt4
IF AA$ = "v" THEN CLM: B 23, 18, "COV...": GOTO Prompt5
IF AA$ = "x" THEN CLM: B 23, 17, "Dist...": GOTO Prompt6
SELECT CASE AA$
  CASE "D": NV = 1: CASE "L": NV = 2: CASE "r": NV = 3: CASE "h": NV = 4
  CASE "B": NV = 5: CASE "d": NV = 6: CASE "n": NV = 7: CASE "o": NV = 8
  CASE "M": NV = 10: CASE "w": NV = 11: CASE "l": NV = 13: CASE "t": NV = 15
  CASE "E": NV = 17:  CASE "Y": NV = 19: CASE "p": NV = 21: CASE "P": NV = 25
  CASE "A": NV = 27: CASE "a": NV = 29: CASE "f": NV = 35: CASE "C": NV = 36
  CASE "R": NA = 13: CASE "S": NA = 14: CASE "W": NA = 15: CASE "e": NV = 31
  CASE "c": NV = 33: CASE "F": NV = 37
  CASE CHR$(32): GOTO FatYldQ: CASE ELSE: GOTO Prompt4
END SELECT
CLM
GOTO EDITT
```

```
Prompt5:
AA$ = INKEY$: IF AA$ = "" THEN GOTO Prompt5
SELECT CASE AA$
  CASE "w": NV = 12: CASE "l": NV = 14:  CASE "t": NV = 16
  CASE "E": NV = 18:  CASE "Y": NV = 20: CASE "p": NV = 22
  CASE "a": NV = 30: CASE "e": NV = 32
  CASE "c": NV = 34: CASE "A": NV = 28: CASE "P": NV = 26
  CASE ELSE: GOTO Prompt5
END SELECT
GOTO EDITT
Prompt6:
AA$ = INKEY$: IF AA$ = "" THEN GOTO Prompt6
SELECT CASE AA$
  CASE "w": NA = 2: CASE "l": NA = 3:  CASE "t": NA = 4
  CASE "E": NA = 5:  CASE "Y": NA = 6: CASE "p": NA = 7
  CASE "a": NA = 10: CASE "e": NA = 11: CASE "c": NA = 12
  CASE "A": NA = 9: CASE "P": NA = 8
  CASE ELSE: GOTO Prompt6
END SELECT
GOTO EDITT

'-----------------------------------------------------------------
FatYldQ:
'
CLM
GOSUB PrintVarname
     '
COLOR 15, 1
B 23, 4, "   Edit again   Fatigue (to bypass Yielding) or <Space> to continue"
COLOR 14, 1: B 23, 14, "E": B 23, 28, "F": B 23, 60, "<": B 23, 66, ">": COLOR
15, 1
Prompt17:
AA$ = INKEY$: IF AA$ = "" THEN GOTO Prompt17
SELECT CASE AA$
  CASE "E", "e": GOTO EditVarble
  CASE "F", "f": yFlag = 1: GOTO Fatigue
  CASE CHR$(32): GOTO MAIN
  CASE ELSE: GOTO Prompt17
END SELECT
'-----------------------------------------------------------------
EDITT:
'
IF NV = 0 AND NA > 12 THEN
  LOCATE 23, 25: PRINT AA$; " = "; ST$(NA)
10  LOCATE 23, 40: INPUT "enter new value -- ", DUM2$
  IF NA = 13 AND (ASC(DUM2$) <> 70 AND ASC(DUM2$) <> 86) THEN
    B 23, 65, " F or V ": GOTO 10
  ELSEIF NA = 14 OR NA = 15 THEN
    IF DUM2$ <> "L" AND DUM2$ <> "M" AND DUM2$ <> "H" THEN
      B 23, 65, " L, M, or H ": GOTO 10
    END IF
    IF (NA = 14 AND ST$(15) = "H") OR (NA = 15 AND ST$(14) = "H") THEN
      IF DUM2$ = "H" THEN
        CLM
```

```
            B 23, 5, "We're not calibrated for the high speed/high sea state."
            B 23, 68, "<Space>"
            COLOR 14, 1: B 23, 68, "<": B 23, 74, ">": COLOR 15, 1
PROMPT8:
            AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT8
            SELECT CASE AA$
               CASE CHR$(32): CLM: GOTO 10
               CASE ELSE: GOTO PROMPT8
            END SELECT
         END IF
      END IF
   END IF
   ST$(NA) = DUM2$
ELSEIF NV = 0 AND NA <= 12 THEN
   LOCATE 23, 25: PRINT "dist'n "; AA$; " = "; ST$(NA)
20  LOCATE 23, 40: INPUT "enter new type --- ", DUM2$
   IF DUM2$ <> "N" AND DUM2$ <> "L" THEN
      LOCATE 23, 65: PRINT " N or L": GOTO 20
   END IF
   ST$(NA) = DUM2$
ELSE
   LOCATE 23, 25: PRINT AA$; " = "; v(NV)
   LOCATE 23, 40: INPUT "enter new value -- ", duml
   v(NV) = duml
END IF
GOSUB PrintValues
CLM
B 23, 26, "<Space> when finished with editing."
COLOR 14, 1: B 23, 26, "<": B 23, 32, ">": COLOR 15, 1
GOTO Prompt4
RETURN
'-----------------------------------------------------------------------------
FatigueScreen:
'_____________
SCREEN 0: COLOR 7, 1: CLS : COLOR 4, 3
B 2, 3, STRING$(77, 220)
B 22, 3, STRING$(77, 223)
FOR I = 2 TO 22
   B I, 2, CHR$(221)
   B I, 79, CHR$(222)
NEXT I
'
B 2, 26, " FATIGUE DETAIL PARAMETERS "
COLOR 15, 1
B 4, 31, ST$(1)
COLOR 7, 1
B 5, 5, "No.  Name    Qty      m     Log C    COV       k     Stress Ratio"
COLOR 14 - (f3Flag * 7), 1: B 5, 18, "Q": B 5, 58, "S": COLOR 7, 1
FOR K = 1 TO nFtypes
   SELECT CASE Ftype$(K)
      CASE "25": nOrd(K) = 1: CASE "33S": nOrd(K) = 2: CASE "36": nOrd(K) = 3:
CASE "4": nOrd(K) = 4
      CASE "10A": nOrd(K) = 5: CASE "20": nOrd(K) = 6: CASE "21": nOrd(K) = 7:
CASE "26": nOrd(K) = 8
```

```
    CASE "39": nOrd(K) = 9: CASE "28F": nOrd(K) = 10: CASE "51": nOrd(K) =
11: CASE "11": nOrd(K) = 12
    CASE "49": nOrd(K) = 13
    CASE ELSE
      nOrd(K) = 13 + newFtypes
  END SELECT
  I# = K: nFdet# = nFdet(K)
  COLOR 14 - (f3Flag * 7), 1: D K + 5, 5, I#, F2$: COLOR 7, 1: B K + 5, 10,
Fdet$(nOrd(K))
  COLOR 15, 1: D K + 5, 18, nFdet#, F3$: COLOR 7, 1
  D K + 5, 23, Fpar(nOrd(K), 1), F23$: D K + 5, 32, Fpar(nOrd(K), 2), F22$
  D K + 5, 40, Fpar(nOrd(K), 3), F13$: D K + 5, 48, Fpar(nOrd(K), 4), F14$
  COLOR 15, 1: D K + 5, 60, Fsr(K), F14$: COLOR 7, 1
  'WRITE #5, I#, Fdet$(nOrd(K)), nFdet#, Fpar(nOrd(K), 1), Fpar(nOrd(K), 2)
  ', Fpar(nOrd(K), 3), Fpar(nOrd(K), 4), Fsr(K)
NEXT K
COLOR 15, 1
IF f3Flag = 1 THEN
  B 23, 42, "<Space> to return to graph screen"
  COLOR 14, 1: B 23, 42, "<": B 23, 48, ">": COLOR 15, 1
PROMPT22:
    AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT22
    SELECT CASE AA$
      CASE CHR$(32): RETURN
      CASE ELSE: GOTO PROMPT22
    END SELECT
END IF
B 23, 38, "Edit, Add detail or <Space> to continue"
COLOR 14, 1: B 23, 44, "A": B 23, 58, "<": B 23, 64, ">": COLOR 15, 1
PROMPT12:
AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT12
SELECT CASE AA$
  CASE "Q", "q"
   CLM
   LOCATE 23, 30: INPUT "Enter row number -- ", duml
   IF duml > nFtypes THEN
    CLM
    B 23, 30, "Enter a row number between 1 and ": WRITE nFtypes
    INPUT duml
   END IF
   CLM
   LOCATE 23, 30: INPUT "Enter Quantity -- ", nFdet(duml)
   GOTO FatigueScreen
  CASE "S", "s"
   CLM
   LOCATE 23, 30: INPUT "Enter row number -- ", duml
   IF duml > nFtypes THEN
    CLM
    B 23, 30, "Enter a row number between 1 and ": WRITE nFtypes
    INPUT duml
   END IF
   CLM
   LOCATE 23, 30: INPUT "Enter Stress ratio -- ", Fpar(duml, 4)
   GOTO FatigueScreen
```

```
   CASE "2": duml - 2: GOTO 40: CASE "3": duml - 3: GOTO 40
   CASE "4": duml - 4: GOTO 40: CASE "5": duml - 5: GOTO 40
   CASE "6": duml - 6: GOTO 40: CASE "7": duml - 7: GOTO 40
   CASE "8": duml - 8: GOTO 40: CASE "9": duml - 9: GOTO 40
   CASE "1"
PROMPT13:
    AA$ - INKEY$: IF AA$ - "" THEN GOTO PROMPT13
    SELECT CASE AA$
     CASE CHR$(13): duml - 1: GOTO 40: CASE "0": duml - 10: GOTO 40
     CASE "1": duml - 11: GOTO 40: CASE "2": duml - 12: GOTO 40
     CASE "3": duml - 13: GOTO 40
     CASE "4"
   IF nFtypes >- 14 THEN
     duml - 14: GOTO 40
   ELSE
     CLM
     B 23, 30, "Enter a row number between 1 and "
     LOCATE 23, 63: WRITE nFtypes
     GOTO PROMPT12
   END IF
     CASE "5"
   IF nFtypes >- 15 THEN
     duml - 15: GOTO 40
   ELSE
     CLM
     B 23, 30, "Enter a row number between 1 and "
     LOCATE 23, 63: WRITE nFtypes
     GOTO PROMPT12
   END IF
     CASE "6"
   IF nFtypes - 16 THEN
     duml - 16: GOTO 40
   ELSE
     CLM
     B 23, 30, "Enter a row number between 1 and "
     LOCATE 23, 63: WRITE nFtypes
     GOTO PROMPT12
   END IF
     CASE ELSE: GOTO PROMPT12
    END SELECT
40  CLM
    B 23, 30, "Quantity or Stress ratio? -- "
    COLOR 14, 1: B 23, 30, "Q": B 23, 42, "S": COLOR 15, 1
PROMPT14:
    AA$ - INKEY$: IF AA$ - "" THEN GOTO PROMPT14
    SELECT CASE AA$
     CASE "Q", "q"
   CLM
   LOCATE 23, 30: INPUT "Enter Quantity -- ", nFdet(duml)
     CASE "S", "s"
   CLM
   LOCATE 23, 30: INPUT "Enter Stress ratio -- ", Fpar(duml, 4)
     CASE ELSE: GOTO PROMPT14
    END SELECT
```

```
    GOTO FatigueScreen
   CASE "A", "a"
    CLM
    IF nFtypes = 16 THEN
      B 23, 2, "No more room.  Exit program and modify text file CGOOF.PAR or"
      B 23, 60, " <Space> to continue "
      COLOR 14, 1: B 23, 61, "<": B 23, 67, ">": COLOR 15, 1
PROMPT11:
      AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT11
      SELECT CASE AA$
        CASE CHR$(32)
      CASE ELSE: GOTO PROMPT11
      END SELECT
      GOTO FatigueScreen
    END IF
    I = 13 + newFtypes + 1: K = nFtypes + 1: I# = K
    COLOR 14, 1: D K + 5, 5, I#, F2$: COLOR 15, 1
    LOCATE 23, 30: INPUT "Designation (number)-- ", IJK
    Fdet$(I) = "X" + MID$(STR$(IJK), 2, 2)
    COLOR 7, 1: B K + 5, 10, Fdet$(I): COLOR 15, 1: CLM
    LOCATE 23, 30: INPUT "Quantity             -- ", nFdet(K)
    nFdet# = nFdet(K): D K + 5, 18, nFdet#, F3$: CLM
    LOCATE 23, 30: INPUT "Slope of S-N, m      -- ", Fpar(I, 1)
    COLOR 7, 1: D K + 5, 23, Fpar(I, 1), F23$: COLOR 15, 1: CLM
    LOCATE 23, 30: INPUT "Intercept, Log C     -- ", Fpar(I, 2)
    COLOR 7, 1: D K + 5, 32, Fpar(I, 2), F22$: COLOR 15, 1: CLM
    LOCATE 23, 30: INPUT "COV of S-N line      -- ", Fpar(I, 3)
    COLOR 7, 1: D K + 5, 40, Fpar(I, 3), F13$: COLOR 15, 1: CLM
    LOCATE 23, 30: INPUT "Weibull param., k  -- ", Fpar(I, 4)
    COLOR 7, 1: D K + 5, 48, Fpar(I, 4), F14$: COLOR 15, 1: CLM
    LOCATE 23, 30: INPUT " Stress ratio        -- ", Fsr(K)
    D K + 5, 60, Fsr(K), F14$
    Ftype$(K) = Fdet$(I)
    nFtypes = K: newFtypes = newFtypes + 1
    GOTO FatigueScreen
   CASE CHR$(32)
   CASE ELSE: GOTO PROMPT12
END SELECT
RETURN
'-----------------------------------------------------------------------
ZeroMessage:
'-------------
SCREEN 9: SCREEN 0: COLOR 15, 1
B 10, 13, "  The Probability of Failing in Yielding is less than  "
B 11, 13, "  the smallest number that the program can compute,    "
B 12, 13, "  which is of the order of 10^(-324)  "
B 23, 60, " <Space> to continue "
COLOR 14, 1: B 23, 61, "<": B 23, 67, ">": COLOR 15, 1
PROMPT21:
AA$ = INKEY$: IF AA$ = "" THEN GOTO PROMPT21
SELECT CASE AA$
  CASE CHR$(32): RETURN
  CASE ELSE: GOTO PROMPT21
END SELECT
```

```
RETURN
'-----------------------------------------------------------------
FileOut:
OPEN "O", 2, "CG" + MID$(STR$(v(38)), 2) + ".out"
OPEN "O", 3, "CG" + MID$(STR$(v(38)), 2) + ".123"
PRINT #2, USING "Run Number  #######,     \                        \"; v(38),
ST$(1)
PRINT #3, USING "Run Number  #######"; v(38)
PRINT #2, "Year     Yielding        Fatigue   Combined: Lower      Upper"
     FS$ = "###     ##.###^^^^      ##.###^^^^         ##.###^^^^
##.###^^^^"
     FL$ = "###   ##.##########^^^^   ##.##########^^^^"
FOR I = 1 TO 30
   PRINT #2, USING FS$; I, Pfy(I), Pff(I, HN), PfSLl1(I), PfSLul(I)
   PRINT #3, USING FL$; I, Pfy(I), Pff(I, HN)
NEXT I
PRINT #2, USING "Displacement =  ####.#,  LWL = ####.##,  Draft = ###.##";
v(1), v(2), v(3)
PRINT #2, USING "Chine length = ####.##,  Chine beam = ###.##,  Deadrise =
###.#"; v(4), v(5), v(6)
PRINT #2, USING " ###  Plates out of ###,  Hydrodynamic Pressure = ###.###";
v(7), v(8), v(9)
PRINT #2, USING "Width,             mean: ###.##,  COV: ##.##, Dist.: \  \";
v(11), v(12), ST$(2)
PRINT #2, USING "Length,            mean: ###.##,  COV: ##.##, Dist.: \  \";
v(13), v(14), ST$(3)
PRINT #2, USING "Thickness,         mean: ##.###,  COV: ##.##, Dist.: \  \";
v(15), v(16), ST$(4)
PRINT #2, USING "Mod E.,            mean: ######,  COV: ##.##, Dist.: \  \";
v(17), v(18), ST$(5)
PRINT #2, USING "Sigma Yield,       mean: ###.##,  COV: ##.##, Dist.: \  \";
v(19), v(20), ST$(6)
PRINT #2, USING "Static Pressure,  mean: ##.###,  COV: ##.##, Dist.: \  \";
v(21), v(22), ST$(7)
PRINT #2, USING "Ship speed, \  \ ###,   Wave hgt, \  \ ###,   M/D Ratio
##.####"; ST$(14), v(23), ST$(15), v(24), v(10)
PRINT #2, USING "Percent of Use,   mean: ##.#,    COV: ##.##, Dist.: \  \";
v(25), v(26), ST$(8)
PRINT #2, USING "Annual use,       mean: ######,  COV: ##.##, Dist.: \  \";
v(27), v(28), ST$(9)
PRINT #2, USING "Wastage,          mean: ###,     COV: ##.##, Dist.: \  \";
v(29), v(30), ST$(10)
PRINT #2, USING "Use in head seas, mean: ##.#,    COV: ##.##, Dist.: \  \";
v(31), v(32), ST$(11)
PRINT #2, USING "Loading cycles,   mean: ######,  COV: ##.##, Dist.: \  \";
v(33), v(34), ST$(12)
PRINT #2, USING "Deformation ratio,  ##.#,  Random number seed, \  \"; v(35),
ST$(13)
PRINT #2, USING "Yielding cycles, ######,  Fatigue cycles, ######"; v(36),
v(37)
PRINT #2, "Type,   Qty,   Slope,   Log C,  COV,   Str. r'o,   Par. k,   Pf30 "
     FS$ = "\    \ ####  ###.###  ###.##  ##.###  ##.###    ##.###
##.##^^^^"
FOR K = 1 TO nFtypes
```

```
  PRINT #2, USING FS$; Ftype$(K), nFdet(K), Fpar(nOrd(K), 1), Fpar(nOrd(K),
2), Fpar(nOrd(K), 3), Fsr(K), Fpar(nOrd(K), 4), Pff(30, K)
NEXT K
CLOSE #2
CLOSE #3
RETURN
'-----------------------------------------------------------------
Break:
'------
SCREEN 0: CLS : END
RETURN
'-----------------------------------------------------------------
ERRoutine:
'----------
SELECT CASE ERR
  CASE 39, 52, 53, 54, 55, 58, 59, 62, 64, 75, 76
    SCREEN 0: COLOR 7, 0: CLS : COLOR 15, 1
    B 10, 10, " There is a file problem.  Make sure that the Data Files are "
    B 11, 10, " correct and in the current drive.                            "
    END
  CASE 61
    SCREEN 0: COLOR 7, 0: CLS : COLOR 15, 1
    B 10, 10, " Disk full.  Save Output aborted.  Press any key to continue."
    Pause$ = INPUT$(1)
    CLOSE #2: CLOSE #3: GOTO ReviewSL
  CASE 5, 11, 14
    matherror = matherror + 1
    IF matherror > 5 THEN
      SCREEN 0: COLOR 7, 0: CLS : COLOR 15, 1
      B 10, 10, " More than five math errors have been recorded.  Restart
the "
      B 11, 10, " program and check the input data.  If the problem persists
"
      B 12, 10, " try rebooting the system.  Press any key to continue.
"
      Pause$ = INPUT$(1)
    END IF
    RESUME NEXT
  CASE ELSE
    ON ERROR GOTO 0
END SELECT
END
'**************************** END OF SUB-ROUTINES ****************************

DEFINT G
SUB B (NRow, NCol, Strin$)
'-------------------------
LOCATE NRow, NCol
PRINT Strin$
END SUB

SUB Binomial (ZONE, AREA, PFP, PfB)
'----------------------------------
PfB = 0
```

```
Z% = ZONE
Ar% = AREA
FOR K = Z% TO Ar%
  dum1 = FACT(Ar%) / (FACT(K) * FACT(Ar% - K))
  DUM2 = dum1 * PFP ^ K * (1 - PFP) ^ (Ar% - K)
  PfB = PfB + DUM2                                              '(5-11)
NEXT K
END SUB

SUB C (NRow, NCol, NSpace)
'------------------------------
  LOCATE NRow, NCol
  PRINT "("
  LOCATE NRow, (NCol + 1): PRINT STRING$(NSpace, " ")
  LOCATE NRow, (NCol + 1 + NSpace): PRINT ")"
END SUB

DEFSNG A-Z
SUB CLM
'-----
COLOR 1, 1: B 23, 1, STRING$(80, 32)
COLOR 15, 1
END SUB

DEFINT G-K, N
DEFDBL A-F, L-M, O-Z
SUB D (NRow, NCol, Value, Format$)
'----------------------------------------
  LOCATE NRow, NCol
  PRINT USING Format$; Value
END SUB

DEFDBL G, N
SUB DesPressure (vel, Dell, Bc, beta, Wht, Lp, Dr, w, 1, Lwl, Ratio, Pd)
'----------------------------------------------------------------------------
Del = Dell * 2240!
Tau = 2!
g = 32.174
Pi = 3.1415926536#
                         'Average of highest 1/10 acceleration at C of G  '(5-6)
N1TEN = 7! * (Wht / Bc) * (1! + Tau / 2!) ^ .25 * (vel * 1.688 / SQR(g * (Del
/ 64!) ^ (1! / 3!))) / (Lp / Bc) ^ 1.25
Ar = 25! * Del / 2240! / Dr                          'Spencer reference area
Af = w * 1 / Ar / 144!
                                                     'Load distribution factor
LDf = .1 + 1! / (8.1 * Af ^ 2 + 15.6 * Af + 1.1)                        '(5-7)
                                           'Bottom design pressure '(5-5)
Pd = LDf * Del * COS(beta * Pi / 180) / 14.55 / Lwl / Bc * (1! + N1TEN)
Pd = Pd * Ratio         'Apply a factor to estimate the mean maximum pressure
END SUB

DEFINT N, X-Y
DEFSNG A-M, O-W, Z
SUB DLINE (Row!, Col!, hv$, leng!, Ncolr)
```

```
'_______________________________________
x = Col! * 8
y = Row! * 14
SELECT CASE hv$
  CASE "h"
  LINE (x, y)-(x + leng! * 8, y), Ncolr
  CASE "v"
  LINE (x, y)-(x, y + leng! * 14), Ncolr
END SELECT
END SUB

DEFINT G-K
DEFDBL A-F, L-M, O-Z
SUB ExtremePressure (P, Pc, Ti, Au, U, nYr, EP, EPsd, an, Un)
'_______________________________________________________________
Pi = 3.1415926536#
N! = (Au * U * .01 * 3600 / Ti) * nYr             'Number of time intervals
IF N! < 1! THEN N! = 2.7182818#                     'To prevent a math error
an = SQR(2 * LOG(N!))                                                '(4-11)
Un = an - (LOG(LOG(N!)) + LOG(4 * Pi)) / (2 * an)                    '(4-12)
EP = (Pc * (Un + (.577216 / an)) + 1) * P      'Mean extreme pressure  (4-13)
EPsd = Pi * Pc * P / (SQR(6) * an)                                   '(4-14)
EPc = EPsd / EP
END SUB

FUNCTION FACT (I)
'_______________
Q = 1
IF I > 0 THEN
  FOR J = 1 TO I
   Q = Q * J
  NEXT J
END IF
FACT = Q                                                 'The factorial of I
END FUNCTION

DEFSNG G
SUB Fatigue (v() ,Cyr(), nFtypes, nOrd(), Fpar(), Fsr(), nFdet(), Pff(),
COVPff(), Hfd())

IF v(37) < 200 THEN CLS
DIM Bin(42), Dist(42)
OPEN "I", 1, "CGOOF.HIS"            ' Read the load histogram data from file
FOR K = 1 TO 42
  INPUT #1, Bin(K), Dist(K)
NEXT K
CLOSE #1
'
Pi = 3.1415926536#
N1& = nFtypes * 15 * v(37): NI = 1                 'A counter for the display
FOR J = 1 TO nFtypes
  FOR I = 1 TO 30: Pff(I, J) = 0: NEXT I
  IF nFdet(J) = 0 THEN GOTO 30
  Sum = 0
```

```
  FOR K = 1 TO 42            'Equivalent Constant Amplitude Stress Range, Sre
    Sum = Sum + Bin(K) ^ Fpar(nOrd(J), 1) * Dist(K)
  NEXT K
  Sre = Sum ^ (1! / Fpar(nOrd(J), 1))                      '(5-15),(5-20),(A.2-6)
                                                'Mean value of Life from S-N Curve, Lbar
  Lbar = 10 ^ Fpar(nOrd(J), 2) * (1000 / Sre / Fsr(J)) ^ Fpar(nOrd(J), 1)
                                             'Evaluate Gamma(1+1/k) by expansion formula
  Fk = 1! + 1! / Fpar(nOrd(J), 4)
  Gamma = SQR(2 * Pi / Fk) * Fk ^ Fk * EXP(1 / (12 * Fk) - 1 / (360 * Fk ^ 3)
- Fk)
  w = Lbar / Gamma                                               'Wiebull parameter, w
  FOR I = 2 TO 30 STEP 2
    PfSum = 0: PfSumSq = 0
    FOR N = 1 TO v(37)                                           'Erase yellow squares
      IF NI = CINT(N1& / 64) THEN                                '
        N2 = N2 + 1                                              '
        NX = (65 - N2) * 10                                      '
        LINE (NX - 10, 112)-(NX - 5, 116), 15, BF                '
        LINE (NX, 112)-(NX + 5, 116), 0, BF                      '
        NI = 0                                                   '
      END IF                                                     '
      NI = NI + 1
      DesL = I * Cyr(N) / 100!                                   ' Design Life
                                                 ' Pf of detail J in year I in cycle N
      Pf1 = 1 - EXP(-((DesL / w) ^ Fpar(nOrd(J), 4)))
      PfSum = PfSum + Pf1
      PfSumSq = PfSumSq + Pf1 ^ 2
    NEXT N
    Pff(I, J) = PfSum / v(37)
    VarPff = ABS(PfSumSq - v(37) * Pff(I, J) ^ 2)
    COVPff(I, J) = SQR((VarPff / (v(37) - 1)) / v(37)) / Pff(I, J)
  NEXT I
30
NEXT J
CLS
END SUB

FUNCTION GofX (w, l, t, Em, SigY, Swp, Wstg, wp)
'________________________________________________
nu# = .3                                                              'Poisson's ratio
nu2# = SQR(1 - nu# + nu# ^ 2)                                   'A recurring argument
tt = t - Wstg
PBeta = (w / tt) * SQR(SigY / Em)           'The plate slenderness ratio, (A.1-1)
                                    'The permanent set ratio when the edge hinge forms
wpo = 1.5 * PBeta ^ 2 / (24 * nu2#)
Rw = wp / wpo                          'The set ratio and non-dimensional function
IF Rw > 1! THEN
  TRw = 1!
ELSE
  TRw = (1! - (1! - Rw) ^ 3) ^ (1! / 3!)
END IF
Qy = 2 / (nu2# * PBeta ^ 2) * (1! + .6 * (w / l) ^ 4)        '(A.1-4)
DQo = (1! + .5 * PBeta * (w / l) * (1! + (w / l) * (3.3 - (1! / PBeta))))
DQo = DQo / (nu2# * PBeta ^ 2)                                        '(A.1-5)
```

```
DQ1 = .95 * ((w / 1) / PBeta ^ .5) ^ 1.5
Q = Qy + TRw * (DQo + DQ1 * Rw)      'The Resistance of the plate, Q    (A.1-6)
GofX = (SigY ^ 2 * Q / Em) - Swp      'Convert to terms of pressure     (A.1-3)
END FUNCTION

SUB GraphF (nFtypes, Ftype$(), Pff(), Hfd(), v(), ST$(), HN)
'
DIM ORDER%(16), O(16)
SCREEN 9: COLOR 15, 1
FOR N = 1 TO 64
  NX = (N - 1) * 10
  LINE (NX + 5, 112)-(NX + 10, 116), 14, BF
NEXT N
  DLINE 10.5, 5, "v", 10.25, 3
  DLINE 20.5, 4.5, "h", 32.5, 3
  DRAW "g4be4h4"
  FOR I = 0 TO 3
   DLINE 10.5 + I * 2.5, 4.5, "h", 1, 3
  NEXT I
  FOR I = 2 TO 7
   DLINE 20.25, I * 5, "v", .5, 3
  NEXT I
  D 21, 2, 0!, ".##"
  D 22, 14, 10, "###"
  D 22, 24, 20, "###"
  B 22, 37, "Yrs"
  B 10, 5, "Pf"
                                          'Sort the fatigue details in descending order
FOR I = 1 TO nFtypes: O(I) = Pff(30, I): NEXT I
FOR K = 1 TO nFtypes
  Min = 10#
  FOR J = 1 TO nFtypes
    IF O(J) < Min THEN
      Min = O(J)
      INDEX = J
    END IF
  NEXT J
  ORDER%(1 + nFtypes - K) = INDEX
  O(INDEX) = 100#
NEXT K
HN = ORDER%(1)
                                                         'Determine scale of graph
dec = .01#
Dum = 1
WHILE Dum > 0
  dec = dec * 10
  Dum = INT(1! / Pff(30, HN) / dec)
WEND
Scale = INT(Pff(30, HN) * dec) / dec + 1# / dec
IF CINT(Scale * dec / 10) = 1 THEN
  D 11, 2, Scale * dec / 10, "#.#"
ELSE
  D 11, 2, Scale * dec / 10, ".##"
END IF
```

```
D 16, 2, Scale * dec / 20, ".##"
B 10, 8, "x"
LOCATE 10, 10: PRINT USING "#^^^^"; dec / 10
'
Kolor = 15
Nline = 11
FOR J = 1 TO 5                          'The display is limited to five details
  IF Pff(30, ORDER%(J)) > 0 THEN
   Kolor = Kolor - 1
   PSET (40, 287)
   FOR I = 1 TO 30
    x = 40 + (I * 8)
    y = 287 - (Pff(I, ORDER%(J)) * 140 / Scale)
    LINE -(x, y), Kolor
   NEXT I
   LINE (384, Nline * 14 - 7)-(408, Nline * 14 - 7), Kolor
   COLOR Kolor, 1
   B Nline, 51, "  Detail "
   B Nline, 61, Ftype$(ORDER%(J))
   COLOR 15, 1
   Nline = Nline + 2
  END IF
NEXT J
COLOR 15, 1
B 2, 32, ST$(1)
B 4, 28, "Fatigue in Frame Details"
B 6, 23, "Probability of Failure Over 30 Years"
B 8, 62, "Run Number:"
D 8, 73, v(38), "######,"
END SUB

SUB GraphSL (PfSLll(), PfSLul(), v(), ST$(), tt, F22$)
'-----------------------------------------------------------------
SCREEN 9: CLS
FOR N = 1 TO 64
  NX = (N - 1) * 10
  LINE (NX, 112)-(NX + 5, 116), 4, BF
  LINE (NX + 5, 112)-(NX + 10, 116), 14, BF
NEXT N
B 8, 1, "Time:       mins"
D 8, 6, (TIMER - tt) / 60, F22$
FOR J = 0 TO 40 STEP 40
  DLINE 10.5, 5 + J, "v", 10.25, 3
  DLINE 20.5, 4.5 + J, "h", 32.5, 3
  DRAW "g4be4h4"
  FOR I = 0 TO 3
   DLINE 10.5 + I * 2.5, 4.5 + J, "h", 1, 3
  NEXT I
  FOR I = 2 TO 7
   DLINE 20.25, I * 5 + J, "v", .5, 3
  NEXT I
  D 21, 2 + J, 0!, ".##"
  D 22, 14 + J, 10, "###"
  D 22, 24 + J, 20, "###"
```

```
  B 22, 37 + J, "Yrs"
  B 10, 5 + J, "Pf"
NEXT J
D 11, 1, 1!, "##.#"
D 16, 2, .5, ".##"
B 10, 48, "x"
'
PSET (40, 287)
FOR I = 1 TO 30
  x = 40 + (I * 8)
  y = 287 - (PfSL11(I) * 140)
  LINE -(x, y), 15
NEXT I
PSET (40, 287)
FOR I = 1 TO 30
  x = 40 + (I * 8)
  y = 287 - (PfSLul(I) * 140)
  LINE -(x, y), 15
NEXT I
                                              'Determine scale of right-hand graph
dec = .01
Dum = 1
WHILE Dum > 0
  dec = dec * 10
  Dum = INT(1! / PfSLul(30) / dec)
WEND
Scale = INT(PfSLul(30) * dec) / dec + 1! / dec
IF CINT(Scale * dec / 10) = 1 THEN
  D 11, 42, Scale * dec / 10, "#.#"
ELSE
  D 11, 42, Scale * dec / 10, ".##"
END IF
D 16, 42, Scale * dec / 10 / 2, ".##"
LOCATE 10, 50: PRINT USING "#^^^^"; dec / 10
PSET (360, 287)
FOR I = 1 TO 30
  x = 360 + (I * 8)
  y = 287 - (PfSL11(I) * 140 / Scale)
  LINE -(x, y), 15
NEXT I
PSET (360, 287)
FOR I = 1 TO 30
  x = 360 + (I * 8)
  y = 287 - (PfSLul(I) * 140 / Scale)
  LINE -(x, y), 15
NEXT I
COLOR 15, 1
B 2, 32, ST$(1)
B 4, 26, "Combined Yielding and Fatigue"
B 6, 23, "Probability of Failure Over 30 Years"
B 8, 62, "Run Number:"
D 8, 73, v(38), "######,"
END SUB
```

```
DEFINT G
SUB GraphY (Pfy(), v(), ST$(), tt, F22$)
'
SCREEN 9
FOR N = 1 TO 64
  NX = (N - 1) * 10
  LINE (NX, 112)-(NX + 5, 116), 4, BF
NEXT N
B 8, 1, "Time:       mins"
D 8, 6, (TIMER - tt) / 60, F22$
FOR J = 0 TO 40 STEP 40
  DLINE 10.5, 5 + J, "v", 10.25, 3
  DLINE 20.5, 4.5 + J, "h", 32.5, 3
  DRAW "g4be4h4"
  FOR I = 0 TO 3
   DLINE 10.5 + I * 2.5, 4.5 + J, "h", 1, 3
  NEXT I
  FOR I = 2 TO 7
   DLINE 20.25, I * 5 + J, "v", .5, 3
  NEXT I
  D 21, 2 + J, 0!, ".##"
  D 22, 14 + J, 10, "###"
  D 22, 24 + J, 20, "###"
  B 22, 37 + J, "Yrs"
  B 10, 5 + J, "Pf"
NEXT J
D 11, 1, 1!, "##.#"
D 16, 2, .5, ".##"
B 10, 48, "x"
'
PSET (40, 287)
FOR I = 1 TO 30
  x = 40 + (I * 8)
  y = 287 - (Pfy(I) * 140)
  LINE -(x, y), 15
NEXT I
dec = .01
Dum = 1
WHILE Dum > 0
  dec = dec * 10
  Dum = INT(1! / Pfy(30) / dec)
WEND
Scale = INT(Pfy(30) * dec) / dec + 1! / dec
IF CINT(Scale * dec / 10) = 1 THEN
  D 11, 42, Scale * dec / 10, "#.#"
ELSE
  D 11, 42, Scale * dec / 10, ".##"
END IF
D 16, 42, Scale * dec / 10 / 2, ".##"
LOCATE 10, 50: PRINT USING "#^^^^"; dec / 10
PSET (360, 287)
FOR I = 1 TO 30
  x = 360 + (I * 8)
  y = 287 - (Pfy(I) * 140 / Scale)
```

```
  LINE -(x, y), 15
NEXT I
COLOR 15, 1
B 2, 32, ST$(1)
B 4, 28, "Yielding in Bottom Plating"
B 6, 23, "Probability of Failure Over 30 Years"
B 8, 62, "Run Number:"
D 8, 73, v(38), "######,"
END SUB

FUNCTION PhiInv (R) STATIC
'______________________________
                    'Inverse of the Normal Distribution function, of probability R
DIM Cfs(8, 4)
x = 1! - R - R
SIGMA = SGN(x)
IF Cfs(1, 2) <> 0 THEN : GOTO 50
Cfs(1, 1) = 0: Cfs(1, 2) = -.57517029#: Cfs(1, 3) = -1.8965133#
Cfs(1, 4) = -.054962605#: Cfs(2, 1) = -.11377303#: Cfs(2, 2) = -3.293474#
Cfs(2, 3) = -2.3749959#: Cfs(2, 4) = -1.1875145#: Cfs(3, 1) = -.11466659#
Cfs(3, 2) = -.13147744#: Cfs(3, 3) = -.2368201#: Cfs(3, 4) = -.050739749#
Cfs(4, 1) = -44.279769#: Cfs(4, 2) = 21.985462#: Cfs(4, 3) = -7.5861027#
Cfs(4, 4) = 0: Cfs(5, 1) = -.0566842208#: Cfs(5, 2) = .39370209#
Cfs(5, 3) = -.3166501#: Cfs(5, 4) = .062089629#: Cfs(6, 1) = -6.2667859#
Cfs(6, 2) = 4.6662627#: Cfs(6, 3) = -2.9628832#: Cfs(6, 4) = 0
Cfs(7, 1) = .00018511591#: Cfs(7, 2) = -.002028152#: Cfs(7, 3) = -.14983844#
Cfs(7, 4) = .010786386#: Cfs(8, 1) = .099529751#: Cfs(8, 2) = .52117329#
Cfs(8, 3) = -.068883009#: Cfs(8, 4) = 0
50
Z = ABS(x)
IF Z <= .85 THEN GOTO Four
Az = 1! - Z
BZ = Z
'Argument is between 0.85 and 1.0 - Obtain transformed variable
ONE:
  w = SQR(-LOG(Az + Az * BZ))
  IF w < 2.5 GOTO Three
  IF w < 4! GOTO Two
'W is greater than 4.0, approximate Erf by a rational function in 1/W
  WI = 1! / w
  SN = ((Cfs(7, 4) * WI + Cfs(7, 3)) * WI + Cfs(7, 2)) * WI
  SD = ((WI + Cfs(8, 3)) * WI + Cfs(8, 2)) * WI + Cfs(8, 1)
  Erf = w + w * (Cfs(7, 1) + SN / SD)
  GOTO Five
' W is between 2.5 and 4, approximate Erf by a rational function in W
Two:
  SN = ((Cfs(5, 4) * w + Cfs(5, 3)) * w + Cfs(5, 2)) * w
  SD = ((w + Cfs(6, 3)) * w + Cfs(6, 2)) * w + Cfs(6, 1)
  Erf = w + w * (Cfs(5, 1) + SN / SD)
  GOTO Five
'W is between 1.13222 and 2.5, approximate Erf by a rational function in W
Three:
  SN = ((Cfs(3, 4) * w + Cfs(3, 3)) * w + Cfs(3, 2)) * w
  SD = ((w + Cfs(4, 3)) * w + Cfs(4, 2)) * w + Cfs(4, 1)
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  Erf = w + w * (Cfs(3, 1) + SN / SD)
  GOTO Five
'Z is between 0 and 0.85, approximate Erf by a rational function in Z
Four:
  Z2 = Z * Z
  Erf = Z + Z * (Cfs(2, 1) + Cfs(1, 2) * Z2 / (Cfs(2, 2) + Z2 + Cfs(1, 3) /
(Cfs(2, 3) + Z2 + Cfs(1, 4) / (Cfs(2, 4) + Z2))))
'Form solution by multiplying Erf by the proper sign
Five:
  Erf = SIGMA * Erf
  PhiInv = -SQR(2) * Erf
END FUNCTION

SUB SeaSpeed (NV, s$, w$, OpCell(), vel, Wht, Ratio, PcUse, Uhs)
'
SELECT CASE w$
  CASE "L"
    SELECT CASE s$
      CASE "L": I = 1: CASE "M": I = 2: CASE "H": I = 3
    END SELECT
  CASE "M"
    SELECT CASE s$
      CASE "L": I = 4: CASE "M": I = 5: CASE "H": I = 6
    END SELECT
  CASE "H"
    SELECT CASE s$
      CASE "L": I = 7: CASE "M": I = 8
    END SELECT
END SELECT
vel = OpCell(I, 1): Wht = OpCell(I, 2)
IF NV = 10 THEN                                                'Allow for editing values
  OpCell(I, 3) = Ratio
END IF
IF NV = 25 THEN
  OpCell(I, 4) = PcUse
END IF
Ratio = OpCell(I, 3)
PcUse = OpCell(I, 4)
IF NV <> 31 THEN
  Uhs = 0
  FOR J = 1 TO 8
    Uhs = Uhs + OpCell(J, 4)
  NEXT J
  Uhs = Uhs - OpCell(I, 4) + PcUse
END IF
END SUB
```

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